DESIGN AND QUALIFICATION TESTS OF THE ON BOARD COMPUTER OF PALAMEDE MICRO SATELLITE

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Abstract

The present work aims at the development of the on board computer of Palamede micro satellite, and at its qualification tests in conditions simulating the orbit environment. The first part of the study deals with the analysis of the space environment in which the computer will be operating, and at the derivation of the required performances of the computer. This analysis, performed by means of numerical simulations, allowed defining a suitable structure to shield the electronic components from the cosmic radiation. The experimental part of the work aimed instead at the qualification tests in vacuum conditions. These tests were performed in a vacuum chamber in the laboratories of the Fachhochschule Aachen in Germany, in which the temperature and pressure conditions have been set to match the expected on orbit conditions. The goal of these tests, besides the verification of the system, is also to verify the possibility to use commercial electronic equipment, not space qualified, for low cost University satellites. The great simplification in the system design and the cost reduction of a similar solution make it very interesting for programs in which the validation of new technologies represents the main design goal.

1. Presentation of the project

The aim of the present work is the qualification of the on board computer of Palamede micro satellite [1], developed within a University program, by means of a series of endurance and performance tests performed in a vacuum chamber at the Fachhochschule Aachen.

The design of the system is based on the requirements of Palamede mission, and has been based on the typical constraints imposed by the space environment.

The on board computer must operate in a hostile environment, whose main characteristics are the presence of cosmic radiation and the lack of atmosphere. The latter condition, equivalent to vacuum since pressure is in the range of $10^{-7}$ mbar, is reproduced on ground in a vacuum chamber, in which all the qualification tests have been performed at the appropriate levels of pressure and temperature to simulate the actual on orbit conditions. The level of cosmic radiation in the target orbit has been considered in numerical simulations performed with the SPENVIS code, developed by the European Space Agency [2], and has allowed defining the appropriate shield to protect the electronic components.

The test campaign has been performed at the Fachhochschule Aachen (University of Applied Sciences). The electronic system has been verified in a vacuum chamber, and its functionality and performances have been verified.

The on board computer of Palamede micro satellite is not made of space qualified equipment, so no component had ever undergone tests in vacuum conditions. Some component had been verified by the manufacturer, in ambient pressure conditions, for the temperature range. Therefore, it has been necessary to test the system performances in the expected operating pressure and temperature conditions.
The complete lack of information concerning the behavior of similar components in space conditions, joined to the necessity to keep the system working in these extreme conditions, made the test campaign equivalent to a certification. In fact the temperatures inferred from the thermal analysis of the satellite represented the starting point for the tests, but the limits reached in the experiments are now the actual design constraint for what concerns the temperatures of the on board electronic components.

One other aim of the tests has been the verification of the level of outgassing of the components and the level of impurities, such as small air bubbles that could explode and damage some component at very low pressures.

The tests have been performed starting from the minimal requirements suitable for the mission, fixed before the tests; on this basis the series of tests has been decided, and the collected data allowed to define the suitability of the system for the particular mission.

It is important to consider that the main objective of the tests is not a real space qualification, since this would require numerous tests, also mechanical, on a large number of parts. Palamede program makes use of commercial hardware to keep the cost low, so the complete qualification is outside the possibilities and the scope of this small University mission. On the contrary, the tests performed must give an indication about the suitability of the designed system and on the reliability of the electronic components used.

The test procedures for the experiments have been in part based on the U.S. Department of Defense standards [3], even though the needs of an academic program have been considered first.

2. The system

The mainboard IDEA AT/3S is manufactured by the Italian company Eurotech s.r.l.[4], the data acquisition board Diamond-MM-16 by the American company Diamond System Corporation [5], and the power supply EPWR104-3 by the Scandinavian Real Time Devices, Inc. [6]. The three modules are connected with the mainboard AT/3S at the top. The best solution from the thermal point of view would require the power supply at the top, so that its aluminum plate could radiate heat in the environment and not on the other boards. However, this solution is not feasible due to the size of the DiskOnChip mounted on the mainboard, which does not allow any board to be
mounted above the mainboard.

In order to isolate as much as possible the power supply, which represents the greatest heat source, from the mainboard, more affected by high temperatures due to the presence of the processor, the configuration with the data acquisition card in the middle has been chosen, as represented in Figure 1.

3. Radiation effects analysis for the electronic components

The analysis of the effects of cosmic radiation of various origins on the electronic components has been performed using SPENVIS software. Based on numerical models of the different radiation types [7], it is possible to collect all the data required to define an appropriate shield to protect the on board computer.

It was decided to perform a complete simulation of the environment, in which the satellite will be operating, taking into account the maximum possible number of parameters and the most precise models. In fact, this represents the only way to obtain accurate solutions, which in turn must be used to size the shield structure that will guarantee the correct in orbit system behavior.

The analysis performed with SPENVIS can be divided in two parts. The first consists in the evaluation of the radiation level on the target orbit, analysis of the trapped particles in the ionized belts (models AP-8, AE-8 [8]), Sun proton flux (model JPL-91), cosmic rays and estimate of their effects on the systems as the satellite moves along the orbit (CREME model). The second part provides maps or spectral analyses from the ionized particles models.

Once the trajectory has been computed, the particle flux can be evaluated in every point along the orbit, and it is possible to use the previous numerical models to integrate the radiation levels on the entire orbit. At this point, it is also possible to add the effects of Sun bursts.

The final part of the analysis consists in the evaluation of the effects of the previously computed radiation. The most relevant parameters are the total ionized radiation dose adsorbed during the mission (evaluated across three different aluminum shields), the linear energy transfer spectrum for cosmic ray particles and the estimate of the possibility of having a single-event upset in some electronic component.

The available data show that the processor, particularly affected by radiation, has operated up to a total level of adsorbed radiation of about 14 Krad. It is important to consider that the performances of an electronic component exposed to radiation decrease rapidly as the radiation increases, until total failure occurs. Therefore the level of 14 Krad must be considered an upper boundary to be kept far enough to avoid any partial failure.

The most relevant consideration in the evaluation of the results deals with the difference between the components used in the present case on board Palamede satellite and the space qualified components. There are at the moment no available data regarding components similar to those selected for this mission, so some problems might arise from components other than the processor.

Considering that integrity remains an important goal to achieve for this mission, the maximum total radiation level adsorbed is fixed at 2.2 Krad, obtained with a 10 mm thick aluminum shield. The radiation level adsorbed is therefore low enough compared to the processor’s limit, so that at least this unit should operate with no major problems.

4. Vacuum chamber tests

The goal of this series of tests has been the verification of the central unit of the electronic system of the satellite, in pressure and temperature conditions simulating the actual orbit.

Vacuum chamber tests have been performed, during which the EPWR104-3 power supply, the IDEA AT/3S mainboard and the Diamond-MM-16 data acquisition board have been operated and their performances and functionality have been checked.
No module tested has been space qualified before, and had never operated in vacuum; even the temperature range qualification tests have been performed, by the manufacturers, in ambient pressure conditions, and therefore do not guarantee operability in vacuum. For this reason, it was necessary to experimentally verify the correct behavior of the boards in different pressure and temperature ranges.

The ultimate goal of the test campaign is the verification that the selected modules could work in vacuum, and at the same time establish their operating temperature limits.

The outgassing of the components and the lack of impurities was also verified, in order to avoid failures due for instance to small air bubbles trapped in the plastic boards and exploding in vacuum.

5. Requirements definition

The ranges of pressure and temperature considered acceptable for the validity of the tests have been obtained by estimating the conditions on the target orbit.

The estimated pressure at the height of 800 km is in the order of $10^{-9}$ mbar, a value too low to be obtained in the test facilities of the Fachhochschule Aachen. The limit pressure that can be obtained is in the order of $10^{-5}$ mbar, considered in any case acceptable for the kind of tests to be performed. In fact, any mechanical or electrical problem in the electronic boards will become evident even at higher pressures.

The temperature limits estimated on the basis of a thermal analysis are, in the operational condition, a minimum temperature of 302 °K and a maximum temperature of 320 °K. On both values a safety margin of 10 °K has been applied.

The pressure and temperature limits required verifying the suitability of the components to Palamede mission are collected in Table 1.

<table>
<thead>
<tr>
<th>TEST</th>
<th>Level of acceptability</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure limit</td>
<td>$10^{-5}$ mbar</td>
<td>3 times the orbit period: 300 minutes</td>
</tr>
<tr>
<td>Temperature limit</td>
<td>±10°C with respect to the on orbit range: from 290 to 330 K</td>
<td>3 times the orbit period: 300 minutes</td>
</tr>
</tbody>
</table>

Table 1: requirements for Palamede mission

The values reported in Table 1 are the nominal ones, and to these some tolerance has to be applied in order to define the validity of the test. The tolerances have been established by comparing the performances of the available instrumentation with the minimal requirements of certification required for the mission. The tolerances accepted are collected in Table 2.

<table>
<thead>
<tr>
<th>Test parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Temperature from 290 to 330 K</td>
<td>Max temp. - 0 K + 5 K</td>
</tr>
<tr>
<td></td>
<td>Min temp. - 5 K + 0 K</td>
</tr>
<tr>
<td>2. Pressure (in vacuum chamber) 1 x $10^{-5}$ bar</td>
<td>+ - 30%</td>
</tr>
</tbody>
</table>

Table 2: parameters range for Palamede mission

6. The test equipment

The main structure used for the tests is the vacuum chamber. It consists in an environment in which the pressure can be reduced down to $10^{-7}$ mbar by means of two pumps. The first pump lowers the pressure in the chamber to a value close to $10^{-5}$ mbar, in a phase called “first vacuum”, and then the second pump is activated to reach the lowest pressures.
The presence of the two pumps to be activated in sequence makes it particularly easy to verify the outgassing of the specimens inside the chamber. It is in fact enough to stop the second pump for a short period (a few minutes) to record the pressure increase caused by the outgassing.

Figure 2 represents a schematic layout of the test chamber, completely designed and realized at the Fachhochschule Aachen.

In addition to the vacuum chamber, a series of other instruments have been used to measure and record the voltage and current on all the lines of the power supply board, and the temperatures of all the boards inside the chamber.

7. Test program

The test program takes into account two fundamental requirements: the need to simulate the actual on orbit conditions and the need to avoid to pass the tolerances limits of the components, once their suitability to the mission has been stated.

Considering the lack of information that could help in the estimation of the behavior of the components in the test pressure and temperature conditions, a rather conservative procedure has been adopted. First, each board has been verified in vacuum and at ambient temperature, and only upon successful completion of these tests, the boards have been verified for combined pressure and temperature ranges. This in order to avoid that a damage in one board could propagate to the others, and to make it possible to isolate and analyze the eventual damage in one board.

First, the vacuum test of the EPWR104-3 power supply board has been performed, and then the Diamond-MM-16 data acquisition board and the IDEA AT/3S boards have been tested. Following successful completion of these preliminary tests, in which no evidence of any failure was found, the test strategy has been slightly modified. In order to increase the time spent in vacuum, it was decided to test at first the power supply alone, then adding to it the data acquisition board and finally adding the mainboard. The highest risk is associated with the presence of some electrolytic capacitor in the power supply board, which could explode at very low pressures, but no evident damage has been recorded.

The test program can be resumed as follows.

- **Phase (1) Initial setup**: all the components are verified in the vacuum chamber, at ambient pressure and temperature. Objectives:
  1. Verify the equipment and the data acquisition system
  2. Demonstrate the compliance with the test requirements
  3. Measure the basic thermal parameters, such as the processor heating
Phase (2) Startup tests: first tests in vacuum conditions and ambient temperatures. Objectives:
1. Verify the power supply, computer and DiskOnchip performances (with measurements of power supply output voltage and efficiency)
2. Check the behavior of the system in vacuum

Phase (3) Complete tests: tests in vacuum conditions and operating temperatures. Objectives:
1. Verify the power supply, computer and DiskOnchip performances (with measurements of power supply output voltage and efficiency)
2. Check the behavior of the system in vacuum during all the operations

The three test phases have been performed in three different hardware configurations, corresponding to increasing system complexity:
- Configuration 1: EPWR104-3 power supply alone
- Configuration 2: EPWR104-3 power supply and Diamond-MM-16 data acquisition board
- Configuration 3: EPWR104-3 power supply, Diamond-MM-16 board and AT/3S mainboard

By the end of the test campaign, all the components have been operating in vacuum for over one hundred hours.

The third phase of the test campaign has been performed only on the completely assembled system. In this phase the performances are verified in the expected operating pressure and temperatures, so it is a simulation of the on orbit performances.

In order to increase the temperature inside the vacuum chamber, an auxiliary structure to propagate heat by radiation has been realized. Figure 3 reports a schematic layout of the structure, and Figure 4 shows a picture of the electronic boards inside the additional heated cylinder. Electric wires have been placed around the aluminum cylinder, and a variable electric current has been used to regulate the cylinder temperature. The inner surface of the cylinder has been painted with black paint to increase the radiated heat.

8. Experimental results

The previously exposed tests led to some important conclusions, in part already anticipated by the data shown.
All the three tested modules have operated in high vacuum conditions with no evidence of mechanical or electrical damage. This represents indeed the most important result since the main objective of the experiments was precisely to check the possibility of using the selected PC/104 boards in the space environment. The answer in this regard is positive.

In order to quantify the successful results the operational limits verified on each component have been reported in Table 3, for the three series of tests.

### Test 1: vacuum conditions and operating temperatures – stand by - no load

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1,40E-05</td>
<td>28,1</td>
<td>236</td>
<td>6,6316</td>
<td>198</td>
<td>29,6</td>
<td>OK</td>
<td>45,8</td>
<td></td>
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<tr>
<td>2,70E-05</td>
<td>28</td>
<td>235</td>
<td>6,58</td>
<td>492</td>
<td>35,5</td>
<td>OK</td>
<td>73,5</td>
<td></td>
</tr>
</tbody>
</table>

### Test 2: vacuum conditions and operating temperatures – program running - no load

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>1,30E-05</td>
<td>28</td>
<td>235</td>
<td>270</td>
<td>6,58</td>
<td>7,56</td>
<td>90,1</td>
<td>68,9</td>
<td></td>
</tr>
</tbody>
</table>

### Test 3: vacuum conditions and operating temperatures –program running – load

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1,90E-05</td>
<td>20</td>
<td>315</td>
<td>365</td>
<td>6,3</td>
<td>7,3</td>
<td>86,4</td>
<td>63,3</td>
<td></td>
</tr>
<tr>
<td>2,00E-05</td>
<td>20,1</td>
<td>531</td>
<td>581</td>
<td>10,6731</td>
<td>11,6781</td>
<td>86,4</td>
<td>63,3</td>
<td></td>
</tr>
<tr>
<td>3,40E-05</td>
<td>20,1</td>
<td>536</td>
<td>583</td>
<td>10,7736</td>
<td>11,7183</td>
<td>83,9</td>
<td>60,5</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: operational limits reached during tests

The second important objective is to establish the limits for the temperatures of the electronic components. The limit temperatures reached by the components in the various experiments are considered the boundary limits admissible for the parts of the satellite in which the electronic components will be fitted. Table 4 collects the limit temperatures.

### TEST 3 vacuum conditions and operating temperatures

(program running – 5V load)

<table>
<thead>
<tr>
<th>T EPWR</th>
<th>T Diamond</th>
<th>T DiskOnChip</th>
<th>T CPU</th>
<th>T chamber</th>
<th>T cylinder</th>
</tr>
</thead>
<tbody>
<tr>
<td>113,3</td>
<td>83</td>
<td>68,8</td>
<td>86,4</td>
<td>33</td>
<td>63,3</td>
</tr>
</tbody>
</table>

### TEST 2 vacuum conditions and operating temperatures

(program running - no load)

<table>
<thead>
<tr>
<th>T EPWR</th>
<th>T Diamond</th>
<th>T DiskOnChip</th>
<th>T CPU</th>
<th>T chamber</th>
<th>T cylinder</th>
</tr>
</thead>
<tbody>
<tr>
<td>116,2</td>
<td>86</td>
<td>72,7</td>
<td>88,4</td>
<td>34,8</td>
<td>62,5</td>
</tr>
</tbody>
</table>

### TEST 1 vacuum conditions and operating temperatures (stand-by – no load)

<table>
<thead>
<tr>
<th>T EPWR</th>
<th>T Diamond</th>
<th>T DiskOnChip</th>
<th>T CPU</th>
<th>T chamber</th>
<th>T cylinder</th>
</tr>
</thead>
<tbody>
<tr>
<td>120,2</td>
<td>89,1</td>
<td>76</td>
<td>93</td>
<td>35,5</td>
<td>73,5</td>
</tr>
</tbody>
</table>

Table 4: temperature limits reached during tests

The last test performed aims at studying the effect on the performances of the power supply of an electric load on the 5V line, the most efficient during the previous tests. This has been studied with the computer active and running a simple program. This condition, CPU and DiskOnChip active and external load, is the most power-consuming test verified in the present campaign.

The test consists in the comparison between three different conditions:
- no external load and computer in stand-by
- external load on the 5V line and computer active
- no external load and computer active

Figure 5 reports the data collected in this test. The data relative to the first condition (no load and computer in stand-by) have been collected in the first 35 minutes, then the second phase (external load and computer active) has been kept for almost two hours, and finally the external load has been disconnected keeping the computer active.

It is possible to notice, analyzing the power request and the output of the computer program running, that the presence of the external load had no effect on the computer operations. Therefore the on board computer has demonstrated, in this case also, to work correctly in one of the most demanding condition in the course of the mission.

The lowest temperatures that could be reached on orbit have not been verified, since the vacuum chamber used could not refrigerate the test chamber below ambient temperature. This is not regarded as a problem, since all system components are certified for temperatures as low as -40°C in atmosphere. It is then assumed that, considering the satisfactory performances verified in the experiments, the components should have no problems at the expected lowest on orbit temperature of +10°C.

![Test in vacuum conditions and operating temperatures](image)

**Figure 5:** Test 3, configuration 3, temperatures, maximum and minimum input power

Some problems have been found in the power supply, in the contemporary use of the 12V and the 5V converters, in the presence of the external load on the 5V line that powers the PC/104 bus. These problems have been analyzed quite deeply, and they can be summarized by a very simple statement: the reduced efficiency found in these tests leads to a voltage range in the two output lines not compatible with the system performances. The cross effect on the two output lines is due to the particular environment, not to any hardware failure.

Overall, the system has behaved as expected, with some performance degradation with respect to the declared performances in ambient pressure. This performance degradation becomes the constraint in orbit conditions.

The reduction in efficiency of the power supply was in part expected, due to the presence of electrolytic capacitors. In conclusion, it can be stated that the EPWR104-3 power module can be used for Palamede mission, but only to power the PC/104 boards. The other devices have to be powered using a different DC/DC converter.

**9. Conclusions**

The main steps of the present work have been the analysis of the space environment on the target orbit, the design of a structure capable of shielding the on board electronic components from the radiation effects, the experimental verification that the system designed will be suitable for the
actual mission. The nature of the Palamede mission led to the selection of commercial electronic components. For the complete electronic system, an aluminum structure 0.01 m thick is inserted in the satellite frame and used as a shield against radiation present along the target orbit. The shield has been computed by using the most advanced computational models of the space environment, as would be done for the design of the larger satellites. This procedure has imposed a compromise between performances and reliability, and the latter prevailed in the definition of the shield, since no destructive test could be performed on ground, due to cost limitations, to discover the actual radiation limits sustainable. The numerical analysis performed has demonstrated that the target orbit is indeed a hard scenario for any electronic component, and this is a further indication that some conservative choices become acceptable for sake of reliability.

The tests performed to qualify the designed system for space use have led to some important conclusion: all the boards have operated in high vacuum conditions presenting no evidence of structural or electrical damage, and this is indeed a considerable result since the first goal is the verification of the acceptability of the selected PC/104 boards in the space environment. The second objective achieved has been the definition of the operational thermal limits for the electronic components. The recorded highest temperatures for each component are considered the upper boundaries for the temperatures of the satellite in the section dedicated to the electronics, and constitute a boundary for the future detailed thermal analysis.

A further objective has been the evaluation of the performances of the modules in environmental conditions similar to the on orbit conditions. The performances of the computer board have suffered no evident performance degradation caused by the extreme environment conditions, while the power supply board has shown an evident performance degradation in the case of contemporary use of the two supply lines at 12V and at 5V. These problems are related one to the other; the reduced efficiency recorded in all the tests has led to a use of the DC/DC converter in a condition in which the power required on the two lines (12V and 5V) is out of its possibilities. Nevertheless, it can be stated that the overall results are positive, and the system as designed can fly on Palamede satellite.

Acknowledgments

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References
