Electric solar wind sail

ESAIL D41.4 Remote Unit test results

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1. Introduction

This document presents the results from the mechanical and thermal testing of the so called Remote Unit, RU, which is a recurrent subsystem of the E-sail spacecraft under the contract FP7-SPACE-2010-1, project no. 262733, AD-1. When necessary, it describes changes in the technical implementation of the tests, with respect to the test plan, AD-2, the structure of which is partly mimicked in this document. Test section by test section, the outcome is commented, and the test given a verdict. It concludes by summarizing to what extent the hardware complies with applicable requirements (see AD-3), and by suggesting design changes with respect to AD-4.

2. Applicable documents

AD-1: “Part B: Description of Work” of final EU E-sail application
AD-2: “ESAIL D41.3: Remote Unit test plan”
AD-3: “ESAIL D41.1: Requirements specification of the remote unit”
AD-4: “ESAIL D41.2: Design description of the remote unit”
(all referring to final versions)

3. Overview of tests

It was decided to manufacture and test only the CG type of the RU (see AD-4). The various tests were conducted in the order given in AD-2's Table 1, except that the vibrations testing was made before the static mechanical testing to benefit from the access to the ZARM facility for this purpose. The initial technical inspection and the ending pull test were conducted at ÅSTC. All other testing was made at DLR, Bremen. At all times, ÅSTC staff , responsible for the testing, was present. At DLR and ZARM, facility engineers assisted in operating equipment and documenting the tests. Occasionally, facility-specific sensors were used together with the project-specific ones described in the test plan, AD-2.

4. Technical inspection

The hardware was realised according to its design, AD-4, with the following and few exceptions.

The multilayer insulation (MLI) for wrapping of the thermal box, was thicker and heavier than anticipated. Partly this was because of a misinterpretation of its specification, and partly because of the need for overlapping tabs, extensive sealing and quite many feed-throughs. The thickness required slots in the MLI to clear the auxtether reels, but no other actions. Together with the control unit and the reels, the MLI contributed to an RU mass increase, countered partially by the savings from, e.g., structural parts and batteries. With a net mass increase of 32 g, the total wet mass of the unit was 645 g. It is estimated that, although the MLI mass could only be reduced by a few grams, the reels and, in particular, the control unit could be reduced to meet and even fall below the overall wet mass design goal of 613 g (see AD-4) in a final design. Most straightforward is to use the same PCB for control and power supply circuitry, but it would be relatively easy also to accommodate the reel motor motion controller circuitry on the same board. This last measure would also permit for a decrease of the height of the thermal box, not only saving structural materials for the box and its MLI, but also for the shading wings.

With these minor deviations, all of which can be easily compensated for, the RU passed the inspection.

5. Vacuum compatibility test

The equipment used for this test was the DLR Bremen Sun simulator chamber, subsequently used for the thermal testing, and the RU was suspended accordingly (see below). With the electrical feedthroughs to this chamber and a good viewing port, there was no need for video monitoring and wireless communication. One auxtether reel was operated, both were fitted with tether mass dummies made of Teflon (see Fig. 1).

The RU passed this test.

6. Thermal test

As with the vacuum testing, the DLR Sun simulator was used. The RU was suspended in 1.0-mm steel wires from four rods, Fig. 1, with its heat shield facing directly towards the main light source – a 1200-W, collimated xenon lamp. In addition, some support was given by a polymer-insulated wire running under the two reel hubs. The chamber was pumped down to about 1 Pa and its walls cooled with liquid nitrogen to cryogenic level, before the first two test runs were made.

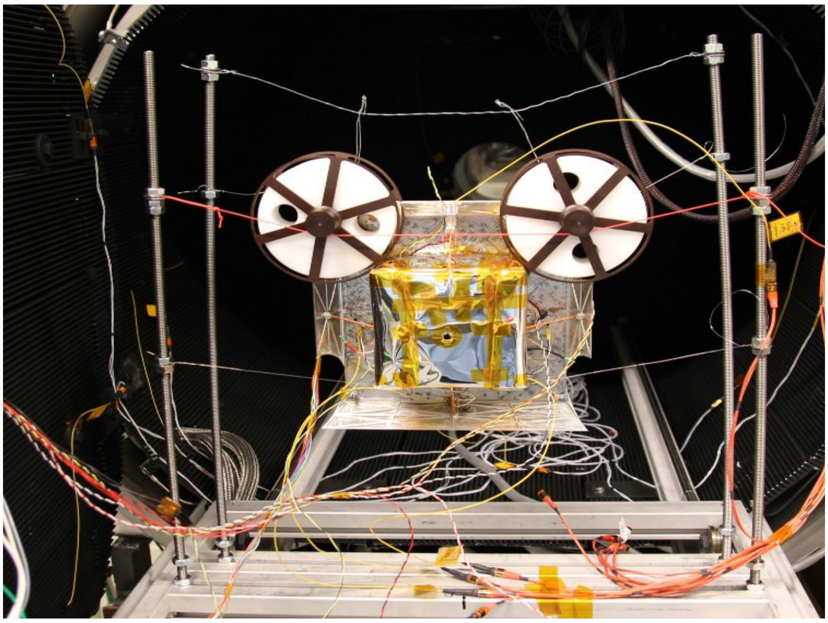

Fig 1: RU suspended for thermal testing. Note thermal box wrapped in MLI, and the auxtether reels with tether dummies.

The first run, intended to simulate conditions at deployment close to 0.9 AU from earth, used the xenon lamp at full power. Temperature sensors at the reel and the radiator registered steady state temperature of 28 and 20ºC, respectively, after 45 and 40 minutes, respectively, Fig. 2.

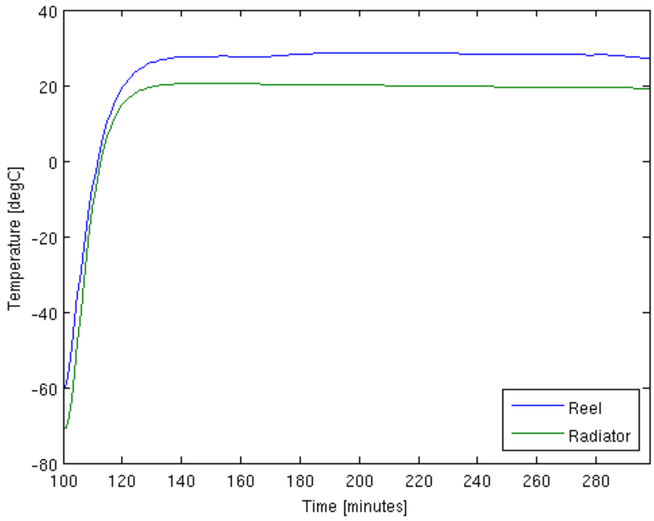

Fig 2: Heat shield temperatures during the first test run.

The temperature inside the thermal box was measured at three different places. The average of these readings is shown in Fig. 3. Since the power dissipation inside the box varied, due to the reel motors being run during the simulated deployment, it is difficult to draw conclusions about the steady state temperature. However, with the temperature being just a little too low when the thermal box was heated with the (low) power available at 4 AU, and power not being an issue at 0.9 AU, it is evident that this is just a matter of temperature control. (Also, see below comment on MLI.)

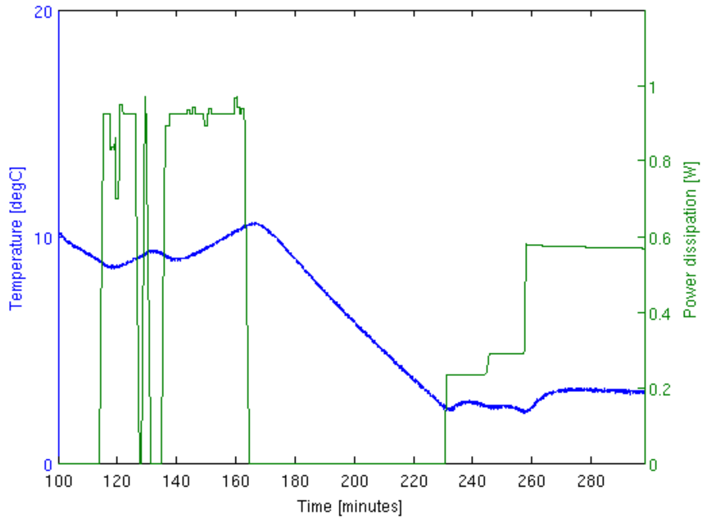

Fig 3: Average temperature and total power dissipation inside the thermal box during the first test run. (The first pulse trains of the green graph show where the reel motor was run at high power. After about t=230 min, the heater is first run at the heating level permitted at 4 AU, then, from t=245 min, the motor is run at low level, and, finally, the heating power is doubled at about t=258 min.)

A limitation with this test run, was that the lamp was not able to give a full 1700-W/m^2 exposure as planned. Instead 1200 W/m^2 was used. In addition, the exposure area barely touched the edges of the RU. It is estimated that a correct exposure would raise the steady state temperatures of the heat shield by approximately 60ºC. (Given the insulation provided with the thermal spacers between the heat shield and the thermal box, the inside temperature of the thermal box will increase negligibly, though.)

In this hot-case simulation, the RU was operated according to plan, but, unfortunately, the solar cells stopped supplying power soon after the xenon lamp was switched on. (Since fully functional solar cells and battery charging were not aimed for, a thorough investigation of the reason for this was not made, but thermomechanical stress of the cells or their inter-connectors is likely.)

For the cold case run, simulating the end of mission 4 AU from Earth and with Sun at a worst-case angle of 60º, a low-power 40-W (average) lamp mounted below the RU at 60º, was used. From the three sensors placed on the heat shield, it can be seen that the non-uniform intensity distribution of the lamp caused large variations in temperature of the heat shield, Fig. 4. The measured steady-state temperatures were -25, -47, and -62ºC for the bottom, middle, and upper parts of the heat shield, respectively.

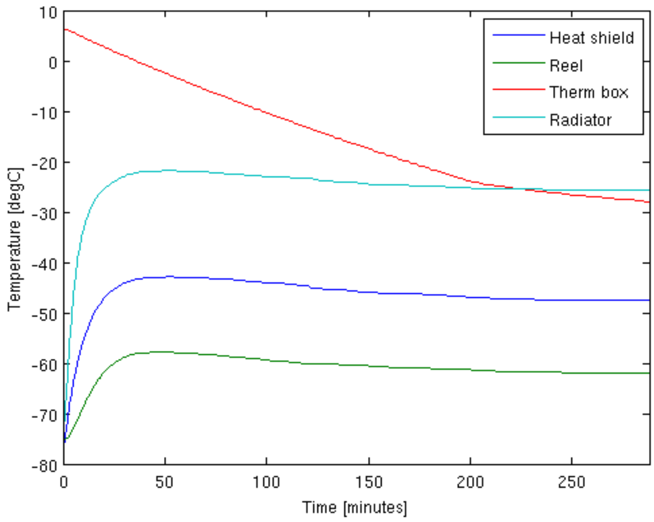

Fig 4: Heat shield and thermal box temperatures during the cold case test.

The test was aborted after five hours, when the temperature inside the thermal box had reached -28ºC. At this point, the thermal box temperature was still decreasing by 1.8ºC/h . By combining simulation and extrapolation of the measured data, it is estimated that the thermal box would reach a steady-state temperature of -40ºC.

Admittedly, the cold-case temperature of the thermal box was lower than anticipated, even when the heater was run with the specified power. Although the present system would allow for a slightly higher heating power, an investigation was made to find the cause of this non-accomplishment. Analysis of the data showed that the overall heat dissipation from the thermal box was 0.90 W at 0ºC and 0.65 W at -20ºC, with only 20-40 mW being lost to the heat shield through conduction in the spacers. This, of course, draws the attention to the MLI.

Later measurements verified that the MLI itself had the expected emissivity of below 0.05, but also showed that the polyimide tape used for sealing and reinforcement of feedthroughs etc, had an emissivity above 0.85 at these temperatures. The polyimide is estimated to have covered around 20% of the surface of the thermal box. More than 90% of this should be easily eliminated or replaceable, since sealing could be made either with metallized tape on the outside or by double-adhesive tape between the MLI layers, and the feedthroughs need not be strengthened several millimetres around them. Hence, the effective emissivity should be reduced by a factor of three or four, which would result in a thermal box steady-state temperature of -17ºC, and 0ºC, respectively. (In addition, it is evident that the insulation should gain much from tightening the feedthroughs and covering the holes made for reel clearance. To fulfil the requirements, this is not necessary, however.)

The final run was that of the turnover, which was to simulate the case where the RU is accidentally flipped to completely expose its normally shaded side to full sunlight. Compared with the test plan, this test was extended by 200% to 15 min, but only increased the temperature by 2ºC inside the thermal box, despite the extended duration and the fact that conditions were worse since the chamber walls were at RT during this run.

The design passed the thermal tests, and the fact that the hardware failed on one point is explained by the excessive use of high-emissivity tape.

7. Vibrational tests

For the vibrational testing, DLR's shaker table was used. For mechanical interfacing, the fixture described in AD-2 was used, Fig. 2, although aluminium and not stainless steel was used for its realisation. Besides testing according to plan, a second run with 25% higher load was made. In no case did any of the strain gauges indicate more than 140 ppm, which should be compared with the 900 ppm where the 7075 aluminium alloy starts to yield. As expected, at all times, the largest strains were recorded at the two heat shield corners where the reels are mounted. (In average, the other strains were below 20 ppm.) No resonances were found.

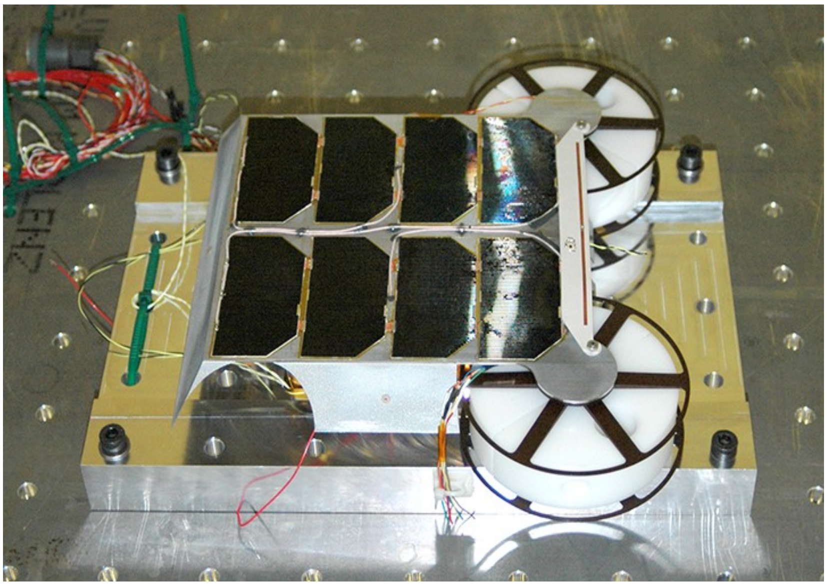

Fig 2: RU mounted with solar cell side up, via its fixture, to the vibrational testing table.

The RU passed this test as well as an extended one.

8. Static loading

For static loading, the centrifuge at ZARM, and the test plan parameters were used. Unfortunately, this didn't allow for use of strain gauges, but the RU was monitored with a live video camera during the test, and inspected for plastic deformation afterwards. No indications of severe elastic or any plastic deformation were observed.

The RU passed this test.

9. Pull test

Before pulling, the axes of the reels were bridged by a stainless steel ribbon yoke, 0.11 mm thick, 14 mm wide, tightened to give a slight compressive strain (approx. 250 ppm) in the reel-facing edge of the heat shield. Then one reel was fixed to the test table and the other pulled with a load increasing in steps of 50 g with dwell times of 1 min. (Both reels were loaded through 25 mm wide steel ribbons where the auxtether would attach.) At a load of about 1.5 kg, the strain was zero (i.e., the bias off set), and at 2.25 kg, the test was aborted because of a sudden but small slip of the ribbon. At that time the recorded strain was 175 ppm. With the well-behaved, linear strain to load dependence and the great margin to plastic deformation, there was no reason to subject the RU to further testing.

Instead of dead weights, the test used spring loading, and instead of a minimum load of 60 g, a gram force of 50 g was used.

The RU passed the test.

10. Conclusions

Given the fact that the test is that of a zero-iteration engineering model, and that the principal objective was not to fulfil all requirements tested against, but rather to gain knowledge about design merits and shortcomings, the result was unexpectedly good, and the proposed design changes indeed minor.

The test implementation was good with a couple of exceptions, the sun simulation being the most severe. Since the power was too low, the effect from the wanted power had to be extrapolated. Moreover, a more uniform and larger field of exposure would have been desired, but, at the same time, the good thermal conductivity of the heat shield ought to give a fast flattening of the temperature profile. Related to this, but intrinsic to the RU itself, was the large time constant for cooling at cool-case simulation of the thermal box interior. Also in this case, an extrapolation was needed to accommodate the test in the testing window and the project budget.

To summarize: All mechanical tests were passed with distinction, the partial failure of the thermal tests is explained by the perhaps somewhat senseless MLI sealing, which is easy to mitigate, the functional tests were all passed except that the solar cells, although not targeted with the testing, stopped charging the batteries. From the inspection, it was learnt that the mass budget was exceeded by about 5%, but it was also argued how this should be compensated for in a second design. This is also the only of the relevant requirements which wasn't fulfilled.

For a future flight model testing, hence, the MLI sealing issue should be fixed, and the thermal testing repeated in a facility outside the consortium, and be allowed an order of magnitude longer duration.

Finally, for future improvement of the RU design, it is suggested that the proposed mass savings are executed, and that the tether reel yoke is finalized.