Design and Development of the Re-Entry Sensor System for the CubeSat Mission SOURCE

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Abstract

With the number of man-made objects being launched into orbit steadily increasing, space debris is one of the big challenges for future space flight. In order to better assess the danger to humans on Earth's surface, re-entry should be researched in more detail. SOURCE serves as a 3U+ satellite platform designed and developed by the small satellite student society (KSat e.V.) and the Institute of Space Systems (IRS) at the University of Stuttgart. It was selected by ESA in 2020 to be part of the 'Fly your Satellite' program, has successfully completed the CDR and is currently preparing for the MRR. SOURCE's objectives are education, verification of several cost-saving, not yet space-proven technologies for orbital use, capturing images of meteoroids entering Earth's atmosphere and documenting its own demise during re-entry by analysing atomic oxygen, heat flux- and pressure data. In order to receive data for as long as possible during re-entry, the satellite switches from S-band to Iridium (inter-satellite link) communication at an altitude below 200 km.

For the in-situ measurement during the re-entry, SOURCE is equipped with two Flux-Phi-Probe (FIPEX) sensors for the measurement of atomic oxygen and five additional sensor arrays. Each array contains one pressure sensor and two heat flux sensors, one commercial and one developed by the IRS. The arrays are placed at five positions in-line across the satellite to reduce effects of tumbling during the re-entry and to allow for the measurement of gradients.

For a first estimation of the expected value ranges, simulations were performed with the software PICLas, developed by the IRS and the Institute of Aero-and Gas Dynamics (IAG) at the University of Stuttgart. In an iterative process, the collected data will be used to further improve this simulation software after the re-entry of the SOURCE satellite.

The aim of this paper is to describe the design philosophy and development process of the sensor readout electronics. The tests carried out are presented and the first results are presented.

Keywords

Re-Entry, CubeSat, Sensors, Tests

Acronyms/Abbreviations

ADC	*Analog Digital Converter*
COTS	*Commercial Off-the-Shelf*
DLR	*German Aerospace Center*
FIPEX	*Flux Phi Probe Experiment*
IRS	*Institute for Space Systems*
KSat e.V.	*Small Satellite Student Society*
MCU	*Microcontroller-Unit*
OBC	*On-Board Computer*
PCB	*Printed Circuit Board*
RTD	*Resistance Temperature Detector*
SOURCE	*Stuttgart Operated, University Research CubeSat for Evaluation and Education*
SPI	*Serial Peripheral Interface*
SSEA	*Symposium on Space Educational Activities*

1. Introduction

The amount of space debris in Earth's Orbit is steadily increasing [1]. Collisions in Orbit, the destruction of two satellites by China and India further amplify this problem, as can be seen in Figure 1. The increasing popularity of Small Satellites and new Satellite Constellations such as Starlink are also responsible for an increasing amount of objects in orbit. Another factor for the increase of objects in orbit are the so called "CubeSats", as this standard also allows small companies and educational institutions to build and launch their own satellites.

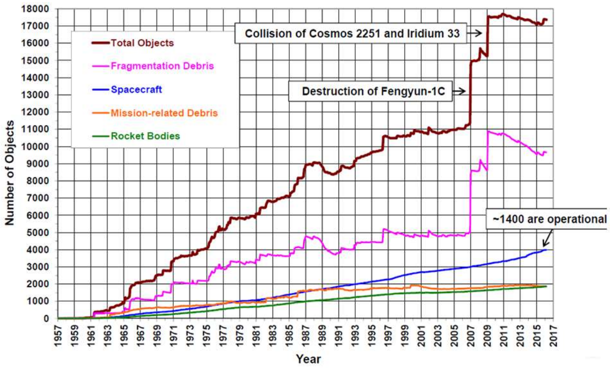

Figure 1. Number of Objects in Earth's Orbit over time [2]

Due to the increasing number of objects in orbit, the number of re-entering objects also increases. Despite this trend, the behaviour of re-entering objects is still not sufficiently investigated.

Although CubeSats are part of the problem, they can help with re-entry research by performing in-situ measurements. This is one of the reasons why the 3U+ CubeSat SOURCE is currently being developed: To gather in-situ data during the re-entry of the satellite. SOURCE is an abbreviation for Stuttgart Operated University Research CubeSat for Evaluation and Education. Additionally to the re-entry sensor setup, SOURCE features a camera system for meteor observation and star tracking, as well as multiple payloads by DLR, Airbus and Fraunhofer IPA for technology demonstration [3].

The mission scenario can be divided into two parts. In the first mission phase begins after the deployment of the satellite. In this phase, meteors are observed and the suitability of the camera system as a startracker is examined. The technology demonstrations will also be tested. As soon as the satellite altitude decreases below 200km, the re-entry sensor system is activated and data is gathered until contact with the satellite is lost. This approach is illustrated in the Mission Scenario in Figure 2.

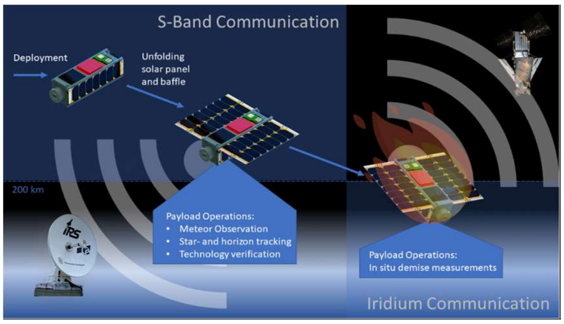

Figure 2. Mission Scenario of SOURCE. Mission Scenario of SOURCE

During the first Phase of the Mission, S-Band is used for communication. During the re-entry phase, communication is switched to Iridium. By using this inter-satellite communication, continuous data transmission can be achieved during the satellite's re-entry phase without the need for a S-Band connection to a specific ground station.

SOURCE is primarily developed and build by students. It is organized by members of the small satellite Student Society (KSat e.V.) and the Institute of Space Systems (IRS) at the University of Stuttgart. Each Subsystem is organized by a student group lead and a PhD supervisor from the institute.

This way, the institute's know-how can be accessed during the development. This know-how results from the small satellite "Flying Laptop", which was launched 2017 and is still in operation [4], as well as from the 6U CubeSat EIVE [5], which is being developed in parallel to SOURCE at the Institute.

Additional support has come from ESA since SOURCE was accepted into the Fly-Your-Satellite programme in 2020.

This paper focusses on the development, build-up and testing of the sensor system for in-situ design measurements.

2. Design of Sensor PCBs

The SOURCE satellite’s sensor system is equipped with 17 sensors for re-entry science. Two Flux Phi Probe Experiment (FIPEX) sensors, located on the front and back of the satellite, determine the amount of atomic oxygen in the upper atmosphere by measuring the electric current caused by the flow of oxygen ions over an electrolyte [6]. They are controlled by three small circular printed circuit boards (PCBs) in the front of the satellite. These PCBs are designed and built by the IRS and tested by the student team.

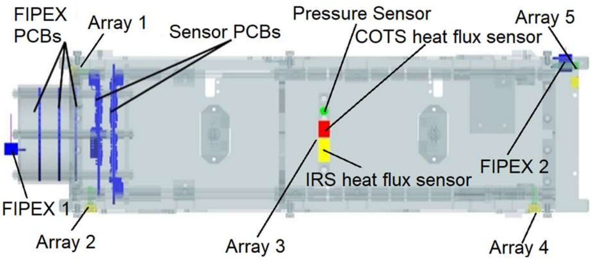

Figure 3. Sensor placement on SOURCE

The remaining 15 sensors are grouped into five arrays shown in Figure 3. Each array consists of one Posifa PVC1000 vacuum pressure sensor, one commercially available Wuntronic FM120-K heat flux sensor, and one heat flux sensor developed by IRS. Each IRS Heat Flux sensor consists of two PT1000 resistance temperature detectors (RTD), whose resistance changes according to their temperature. The RTDs are coated with materials of different catalytic properties, which will result in different recombination rates of dissociated molecules in the hot plasma during re-entry and therefore produce different temperatures [7]. To determine the resistance of the RTDs, a Wheatstone bridge converts their resistance to a differential voltage which is subsequently amplified by an instrumentation amplifier and digitized via an ADC. The heat flux can then be calculated from these temperature measurements. To improve the accuracy of the measurement, the supply voltage of the Wheatstone bridge is also measured via an ADC. The commercial FM-120K heat flux sensors consist of a thermocouple and a thermopile. A thermopile produces a voltage which is directly proportional to the temperature difference of the sensors top and bottom side. This voltage is then amplified by an instrumentation amplifier and digitized via an ADC. Because the thermal conductivity of the sensor is known, the heat flux can be easily derived from the temperature difference. The thermocouple measures the temperature. The PVC1000 pressure sensors operate according to the Pirani measuring principle [8],[9]: A heated measurement resistor is exposed to the atmosphere and supplied with a constant heating current. As the pressure of a low-pressure gas changes proportionally to its thermal conductivity, the temperature of this resistor will change as well according to its surrounding pressure. This will affect the sensor’s resistance, which is calculated by measuring the voltage via Ohm ’s law. The accuracy of the constant current source is the single most important factor for the accuracy of the pressure measurements.

The control electronics of these 15 sensors are housed on two 4-layer PCBs located behind the FIPEX-PCBs. Due to space constraints, both sides of both PCBs contain components. As only one side of a PCB can be reflow-soldered at the KSat workshop, the second side was hand-soldered. Components which were deemed exceedingly difficult to hand-solder were therefore placed on the front side. Due to concerns about tin whisker growth in the space environment [10], lead-based solder was chosen.

A radiation-hardened VA10820 microcontroller communicates via an SPI bus with 8 ADS8343E Analog-to-Digital-Converters. An RS485 bus receives and sends data from and to the On-board Computer (OBC) of the satellite and a JTAG-Bus is used to program the VA10820. This JTAG-bus will be connected to the maintenance port of the satellite and will therefore allow for testing and debugging of the re-entry sensor system on the assembled satellite even if the OBC is off or not working.

3. Test Preparations

Fundamental to verifying the design and functionality of the sensors and their respective systems in space conditions is a thermal-vacuum-test. This is because the test simulates key conditions of a space environment, such as vacuum-level pressure and cycling through significant temperature ranges, however not realistic radiation conditions. It is the first time the system is subjected to realistic operating conditions. Functional and thermal-cycle tests were conducted for two tested systems: one being the FIPEX sensors with a PIC24 microcontroller-unit (MCU) and the second being the re-entry sensors combined with their Vorago microcontroller, both MCUs on respective PCBs. The chamber used for the tests was the IRS thermal-vacuum-chamber, depicted in Figure 4**.**

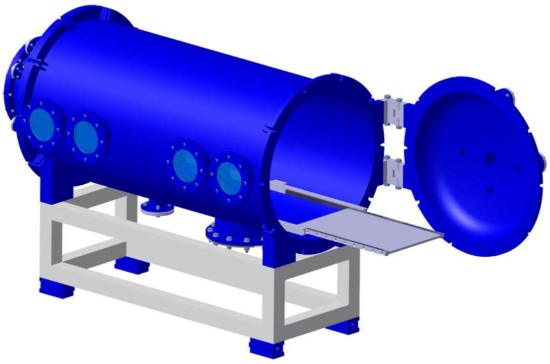

Figure 4. Representation of the thermal-vacuum-chamber at IRS

To enable the communication between the computer and the MCU, the FIPEX system used a custom RS422 to USB board and the software “HTerm”. The PIC24 uses a fixed list of pre-programmed 6-byte commands, which are used to either set a specified sensor to a certain temperature or request the current read-out of data, for which the PIC24 returns a string of 27 bytes.

After initial issues, the connection of the Vorago Payload MCU could be successfully established using a JLink debugging probe. The setup in the chamber led to further problems as the JTag connection only allows cable lengths under 30 cm. This was solved by putting the debugging probe inside the chamber. In the flight setup, the main communication will be handled through RS485, which supports longer cable lengths.

The chamber itself is a tubular chamber that can be opened at one end. The external circulation thermostat “Lauda Proline RP855” brings the mounting plate to the desired temperature via a cooling cycle using the coolant Kryo 51. Through two successively activated pumps a pressure in the lower 10^{-5} mbar range can be achieved.

4. Test Execution

The tests for the FIPEX system and the re-entry sensors on the payload PCBs were carried out separately, as will be their description in this section.

The first tests conducted were the thermal cycles. The thermal simulation for SOURCE predicts temperatures between 1°C and 15°C with uncertainties of ±10°C. The storage temperature ranges of the components are between -40°C and 85°C. The operational temperature of the payload PCBs is -40°C to 80°C, for FIPEX it is -30°C to 60°C. With the component temperature ranges much broader than the expected temperature range, these were the values used for the temperature cycle. The thermal plate must be set to a higher or lower temperature to reach the desired values. This difference comes from the compensation necessary for balancing the thermal radiation from the chamber from which the experiment cannot be shielded completely. In vacuum, there is no heat transfer via convection, meaning the system needs some time to dwell to reach a uniform temperature. The dwell times were up to 12 hours to ensure an even temperature distribution. The thermal cycles were performed in accordance with ESA standards [11].

The thermal cycle for the payload PCBs started with a functional test at room temperature inside the thermal vacuum chamber at a pressure of approximately 10^{-5} mbar. The PCBs were then heated to the maximum operational temperature and the maximum storage temperature. At the maximum operational temperature, a functional test was performed. The first functional test at minimum temperature was conducted a few degrees above -40°C, as the required temperature of the cooling plate was miscalculated. This was corrected for the following cycles. All in all, the cycle of the operational temperature range was executed three times with functional tests at the peaks. The functional test worked as expected. Figure 5 below shows the temperature of the two PCBs during the thermal cycle as measured by Pt1000 sensors glued to the PCBs.

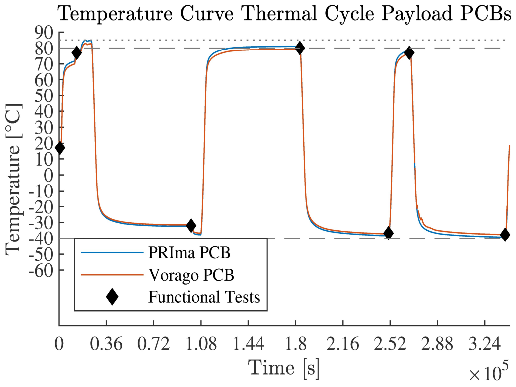

Figure 5. Temperature Curve Thermal Cycle

FIPEX' thermal cycle test consisted of 7 cycles ranging from -40°C to +85°C. To achieve the extreme temperature on all components, the thermal plate was determined in the first cycle to be having to be cooled to -70°C and heated to +100°C respectively. With a narrower operational temperature range, functional tests were conducted during the first cycle at -30°C, room temperature and +60°C. The graph of the temperature profile can be depicted similarly to that of the Payload PCBs.

After completion of the cycles, further functional tests with varying voltages were conducted on the FIPEX system. During the last test, the measurement was run for a total of 30 mins to confirm long-term measurements to be possible. The system passed all tests as functional. However, FIPEX requires a significant amount of power due to the heating of the sensors during measurement. The power consumption measured during each of the functional tests revealed a much higher power consumption than expected during the design phase.

The long-term test for the payload PCBs was also performed. During re-entry, the payload PCB has to run for six to twelve hours. At this time, the microcontroller will continuously read the sensor outputs. For the test, the MCU ran for over 15 hours inside the chamber.

The calibration of the re-entry sensors was also part of the tests. As the pressure sensor of the chamber is not exact enough, a MicroPirani 905 was ordered to be the reference sensor. Communication was established, but it could not be used as it had to be zeroed at a pressure below 10^{-5} mbar. This was not possible because the pressure sensor of the chamber was not exact enough to ensure this value. An alternative setup is under design to zero the reference sensor. When this is concluded, further calibrations for the pressure sensor can be conducted.

The commercial heat flux sensor, a Wuntronic FM-120-K, can measure bidirectional heat flux as well as temperature. To calibrate the temperature, we used a dry-well calibrator. The heat flux calibration was conducted by gluing Pt1000 temperature sensors to both sides of the heat flux sensor. One temperature sensor was also attached to the cooling plate. With different temperatures and different temperature gradients, measured by the Pt1000 and the known transfer surface area, the heat flux can be calculated, and the sensor calibrated. The setup is shown in Figure 6.

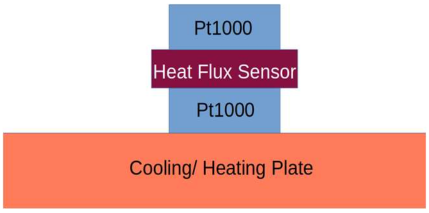

Figure 6. Heat Flux Sensor Setup

The heat flux sensor by the IRS consists mainly of two Pt1000 temperature sensors. These were also calibrated using the dry-well calibrator and the cooling plate.

The analysis of the calibration results is ongoing.

5. Discussion

5.1. PCB Design

Although great care was taken in the selection of components with regard to radiation tolerance and flight heritage, not all parts could be selected according to these criteria.

For instance, some of the voltage converters installed are without radiation tolerance or flight heritage. Here, there were simply no components found that fulfilled these criteria.

As SOURCE is a student project, testing components for radiation tolerance or resorting to radiation-hard parts is not feasible.

For this reason, risks must be taken in this regard. These risks are attempted to be reduced by implementing redundancies.

5.2. Test Results

The qualification tests, the thermal cycle and the long-term test, of the payload PCBs were concluded successfully. Further long-term tests will be performed to ensure reliability and to investigate power requirements and heating of the PCBs in more detail.

The results of the calibration tests are less stringent. The calibration of the pressure sensor is still to be done. The commercial heat flux sensor shows the same heat flux curves as the calibration data, only the amplification seems to be a bit off. It will be examined, whether this is due to the calibration data or the amplification of the sensor. The temperature values of the commercial sensor are of now not coherent, further calibrations will be conducted with the dry-well calibrator. As the vacuum chamber is not needed for this, this test can be performed very easily.

6. Conclusion

The PCB design for the atmospheric re-entry sensors is now almost complete. Initial functional tests show the functionality of the system, even under vacuum conditions. Flight heritage or radiation hardness was considered in the selection of the components used, but this could not always be taken into account.

It is quite likely that the system will survive the two-year stay in space, but this cannot be said with certainty.

The thermal-vacuum tests, even though there were obstacles to overcome, proved successful. Both the Payload PCBs and sensor arrays as well as the FIPEX system could be confirmed to withstand both the vacuum and thermal conditions expected for them during operations.

FIPEX' excess of its initially expected power consumption now needs to be assessed and taken into consideration for the power budget of the satellite in different operating modes. It is unlikely to prohibit use of the sensors however it may affect simultaneous operation with other power-hungry systems.

The only thing missing now for the re-entry sensors is the software for communication with the OBC and the production of the flight model. The FIPEX and the pressure sensors also still need to be calibrated. This step is set to take place in August 2022, closer to the date of launch.

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