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Design and Development of a PS4-OP Payload for Solar Spectral Irradiance Measurements and Technology Demonstration of Small-Satellite Subsystems

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ABSTRACT

This article describes the design and development of INSPIRE-0, a payload on the spent stage of the ISROs PSLV. Recently, the Indian Space Research Organisation (ISRO) released an announcement of opportunity inviting proposals to develop payloads that can be tested on the PS4-Orbital Platform (PS4-OP). This platform is a novel idea formulated by ISRO to use the spent fourth/final stage of the Polar Satellite Launch Vehicle (PSLV), called the PS4, to conduct in-orbit scientific experiments and technology demonstration of small-satellite subsystems. INSPIRE-0 is a PS4-OP payload, jointly developed by the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado Boulder, the Indian Institute of Space Science and Technology (IIST), and the Nanyang Technological University (NTU) in Singapore. This payload has two main objectives. Firstly, the scientific objective is to characterize the solar spectrum using a novel sensor, developed by NTU, that has a wide frequency range from visible to near the infra-red region. The specific objective of the INSPIRE-0 payload is to demonstrate that accurate Solar Spectral Irradiance (SSI) continuous measurements are possible using new compact and robust disruptive technologies. A successful demonstration will pave the way for a future constellation of CubeSats that will provide a very cost-effective way to monitor the Total Solar Irradiance and SSI of the sun in the various spectral bands. Secondly, the INSPIRE-0 payload aims to flight qualify the in-house developed subsystems for the INSPIRESat-1 small satellite mission, namely, the Command and Data Handling (C&DH) Subsystem and the Electrical Power Subsystem (EPS). The article first describes the systems architecture of the payload which has a size of 15cm x 10cm x 7.5 cm, a mass of 1kg, and power consumption of 1.75 W. This is followed by the details of the science instrument and an overview of the different subsystems, namely the C&DH, the EPS, and the PS4-OP interface board. The article concludes with the details of the testing, including comprehensive performance tests and environmental tests, performed to prepare the payload for a planned launch on the PS4-OP in the third quarter of 2021.

Introduction

Recently, the Indian Space Research Organisation (ISRO) released an announcement of opportunity inviting proposals to develop payloads that can be tested on the PSLV 4th Stage Orbital Platform (PS4-OP).[1] Conventionally the final stage of typical launch vehicles are rendered useless after the completion of the mission, acting as space debris till their re-entry burn. By re-purposing the spent PS4 stage as an orbital platform that can provide a payload with power, a communication interface, attitude stabilisation and control, ISRO has provided a unique opportunity to develop payloads that can perform in-orbit experiments, while remaining fixed to the PS4-OP.[2] Previously three PS4-OP payloads have been tested in the orbital platform of the PSLV-C45 (launched in April 2019) which include the Advanced Retarding Potential Analyzer for Ionospheric Studies (ARIS) developed by IIST, experimental Automatic Identification System (AIS) payload by ISRO and Automatic Packet Repeating System (APRS) developed by AMSAT.[3]

The INSPIRE-0 (IS-0) is a PS4-OP payload, jointly developed by the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado Boulder, the Indian Institute of Space Science and Technology (IIST) and the Nanyang Technological University (NTU) in Singapore. Table 1 summarizes the key specifications, science objectives and technology demonstration objectives of this payload, which are described in detail in this paper.

Table 1: IS0 Payload Specifications

Dimensions	150mm x 100mm x 75mm
Mass	1 Kg
Power Consumption	1.75W (5V, 0.35A)
Science Objective	To demonstrate that accurate SSI continuous measurements are possible with small satellites using new compact and robust disruptive technologies.
Technology Demonstration Objective	To flight qualify functionalities of custom designed C&DH and EPS boards .
Science Instrument	Four spectral sensors: AS72651,2,3 and VEML6075. Measurement Range: 20 frequencies: 330nm to 940nm. Precision: 28.6 nW/cm2 Accuracy: +/-12 percent
Command and Data Handling	Microsemi SmartFusion2 SoC FPGA 8 Kb Flash Memory, 2 SD Cards
Electrical Power System	3.3V, 6V, 12V regulators, Voltage and Current sensors

Science Objective

The role of solar variability in Earth's climate variability remains a topic of considerable scientific and societal importance. It is necessary to have a long term record of the solar variability. Solar radiation is important for climate studies since the incoming solar flux is absorbed at different layers of the atmosphere.[4] Hence, quantifying the solar radiation and outgoing long wave radiation of the Earth is necessary for understanding the energy balance of the Earth. Due to changes in solar activity or in the Earth's orbital parameters, the incoming solar radiation at the top of the atmosphere fluctuates over a wide range of temporal scales, from the 27 day rotational cycle to thousands of years. It also includes 11 year solar cycles and cycles of the order of hundreds of years, called "grand solar minima" and "grand solar maxima". Climate models require time varying solar spectra as forcing functions with the available information often based on solar reconstructions and solar models. There is clear evidence showing that solar variability has been a key forcing function in the history of the Earth's climate.[5] However, most of the apparent correlations and associated solar signals tend to be very variable and intermittent. Some are also very difficult to reproduce in climate models.

Establishing a quantitative forcing–response relationship for the Sun–Earth link is problematic without a clear understanding of the key mechanisms engaged in the action of solar variability on the atmosphere and climate, notably at regional scales. There is no general consensus on those mechanisms. The relative variations in incoming Solar Spectral Irradiance (SSI) increase very rapidly with decreasing wavelength in the UV range and below. For instance, over an 11 y cycle, the Total Solar Irradiance (TSI) fluctuates by about 0.1 percent (1.4 W/m2), whereas, in contrast, the radiative flux in the 200nm region, a key spectral window for stratospheric ozone photochemistry, varies by several percentage. This has important implications for the way variations in incoming solar energy are redistributed among the different atmospheric layers.[6] The exceptionally weak Solar Cycle 24 and the future Solar Cycle 25 (expected to begin in late 2019) are interesting periods in this context as they might possibly imply the beginning of a general negative solar forcing.

The absolute value of UV SSI and its variability during more than one decade are also challenging. Accurate observations are fundamental to consolidate the reconstruction models of the solar spectral irradiance. Spectral And Total Irradiance REconstruction for the Satellite Era (SATIRE-S)[7] highlights a weak long term trend (Fig. 1) of UV solar spectral irradiance over the past 40 years for solar minima (inter-cycles), which can be real or not.

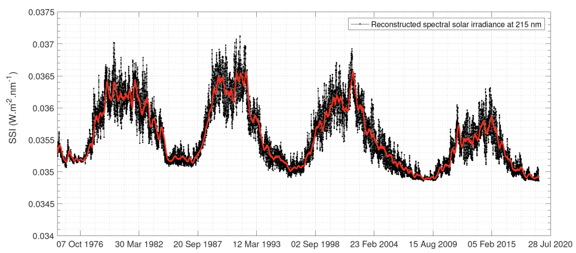

Figure 1: UV solar spectral irradiance at 215nm over the past 40 years from the SATIRE-S model

The relevant long term scientific goal of this mission is to demonstrate the ability to detect any long term trend with a target stability per decade of 3.4 10-5W/m2/nm at the spectral bands listed below in the next section. The specific objective of the IS-0 payload is to demonstrate that these accurate SSI continuous measurements are possible with small satellites using new compact and robust disruptive technologies. A successful demonstration will pave the way for a future constellation of cubesats that will provide a very cost effective way to monitor the TSI and SSI of the sun in the various spectral bands.

Science Payload

The IS0's scientific payload consists of three sensors; the AS72651, the AS72652, and the AS72653 that can detect light from 410nm (UV) to 940nm (IR).[8] In addition, 18 individual light frequencies can be measured with precision down to 28.6 nW/cm2 and accuracy of +/-12 percent. The board also features the VEML6075 UV sensor in two frequency channels of 365 and 330 nm.[9] Together the sensor array provides the ability to measure and characterize the solar output in 20 different frequencies of light from 330 nm to 940 nm. The sensor array is called "Pico Solar Irradiance Monitor" or PicoSIM. The PicoSIM has undergone calibration tests at the National Institute of Standards and Technology facility and hence the measured irradiances are calibrated against spectral responses from the SORCE and other solar irrandiance measurements. Hence, the output from the PicoSIM board has great potential in being able to be used for finding the energy output of the sun in the 20 channels, that the spectrometer can measure it in.

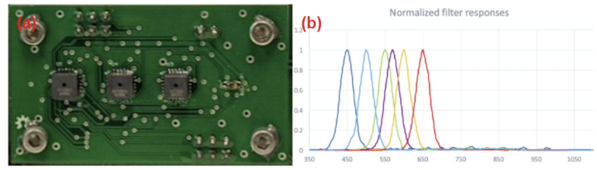

Figure 2: (a) IS0 Pico SIM Payload Board, (b)Normalised Filter response of Payload Board

The board has been designed and built by students from the Nanyang Technological University in Singapore and the Indian Institute for Space Science & Technology along with research guidance from scientists at the University of Colorado. The opportunity to fly this payload represents an opportunity for students to make solar irradiance measurements. The students would be able to compare output from the COTS spectrometer with calibrated on-orbit solar monitoring instruments on the Parker Solar Probe, TSIS and SORCE solar missions.

IS-0 Subsystems Overview

In addition to the PicoSIM sensor board, the IS0 payload consists of three other boards which are the Command and Data Handling(C&DH) Subsystem, the Electrical Power Subsystem (EPS) and the PS4-OP interface board. The PicoSIM sensor board is mounted on the PS4-OP interface board via standoffs (Fig. 3(a)). The payload has approximate outer dimensions of 150 x 100 x 75 (mm), a mass of 1 Kg. and peak power consumption of 1.75W (5V, 0.35 A), satisfying the requirements imposed by the PS4-OP.

The three boards (C&DH, EPS and the PS4-OP interface board) of the payload are connected to each other using a PC104 standard cubesat bus. The PS4-OP interface board provides pigtail leads for the power and data interface with the PS4-OP. As shown in the system level block diagram(Fig. 3(b)), the IS-0 payload requires an 5V supply from the PS4-OP. The peak power consumption of the the payload is 1.75 Watts (5V, 0.35A). The PS4-OP interface board also contains a 5V to 8V boost converter that is used to power the EPS board. The EPS then distributes the power to the other boards, while monitoring their current and voltage. In order the send the telemetry data to the PS4-OP, an RS485 interface is provided. All the data interfaces (from the sensor board, RS485 transceiver and the EPS board) are connected to the C&DH board using a PC104 bus. The C&DH board contains a System-on-Chip(SoC) FPGA which has a embedded micro-controller that runs the flight software. Further details of each of

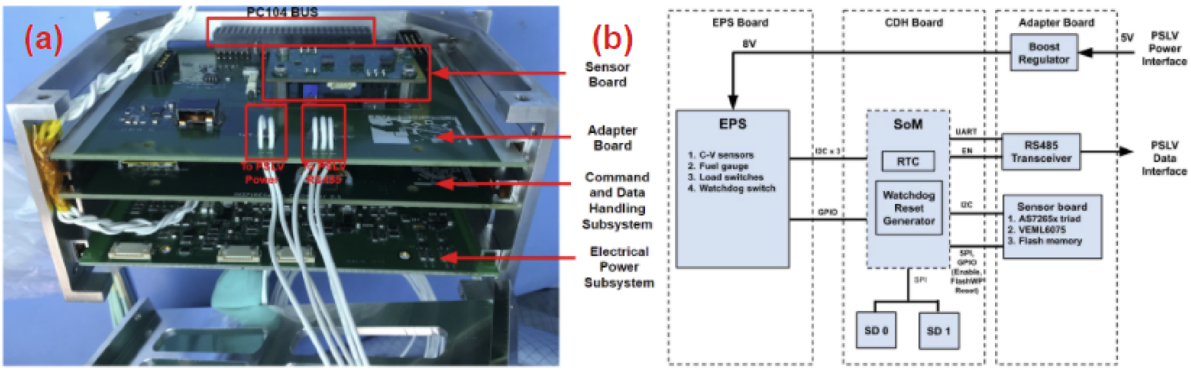

Figure 3: (a) IS0 Flight Model Assembly, (b) IS0 Block Diagram

board are presented in the next subsections.

Command and Data Handling Board

The Command and Data Handling subsystem for the IS0 mission is derived from the INSPIRESat-1 mission.[10] The OBC designed contains a commercial System On Module (SOM), mounted on a flight card as shown in Fig. 4(a). The SoM includes the SmartFusion2 SoC FPGA from Microsemi in a FG484 package, on-module clocks and PLLs, a 64 MB LPDDR SDRAm and a 16 MB SPI Flash on a single module.[11] Due to the power efficiency of the Microsemi SmartFusion SoC FPGA the average power consumption of the board is approximately 0.9 W. The OBC also contains two 128 Gb SD cards, which are used to store science and housekeeping data before they can be downlinked. The board is powered via a single 3.3V supply and provides appropriate interfaces to collect the science and housekeeping data from the EPS and the PicoSIM boards. The board also contains a multilevel reset mechanism that can be used to trigger two levels of resets. The first level is an autonomous reset of the OBC's SoM, that is generated if the flight software is stuck in any software routine. The second is an autonomous reset of the complete payload which involves sending a signal to the EPS board in order to generate the reset.

Electrical Power System Board

The flight model of INSPIRESat-1 EPS is repurposed to act as the Electrical Power System (EPS) board of the INSPIRE-0 payload. A 3.3V buck converter will be used for to power the OBC during the entire mission. Other converters present on the board will also by flight qualified and tested throughout the payload operations. This will be done by turning ON and OFF the converters and monitoring the voltage and current using sensors present on the board.

PS4-OP Interface Board

The PS4-OP interface board for the INSPIRE-0 payload acts as an interface between the IS0 payload and the PS4-OP. The IS-0 payload assumes that the PS4-OP would be providing a 5V power interface and a RS485 data interface to the payload. Thus, the PS4-OP interface board contains a typical RS485 driver that is used to send data to the orbital platform telemetry channel. The power interface (5V and GND) and data (RS485 A, RS485 B and GND) interface are provided as pigtail leads passed through strain relief holes. The board also contains the interface with the sensor board (which is mounted using stand-offs) as well as a solid state relay power enable for the sensor board.

Flight Software and Sequence of Operations

The flight software for IS-0 is written in C as a sequential program. The C code runs on the ARM CortexM3 microcontroller implemented in the Microsemi SmartFusion2 SoC (System on Chip) FPGA. The FPGA implements interfaces with the PicoSIM sensor board and the EPS board. Apart from the peripherals for interfacing, custom developed verilog cores are also implemented in the FPGA, including a Watchdog Timer Handler, a Real Time Counter and a PS4-OP Telemetry Handler. The flowchart shown in Fig. 5 shows a flowchart, summarizing the entire flight software sequence of operations of the IS-0 payload.

Immediately after power ON the initialization procedure takes place. This includes initialization of the various memories, peripheral drivers, software

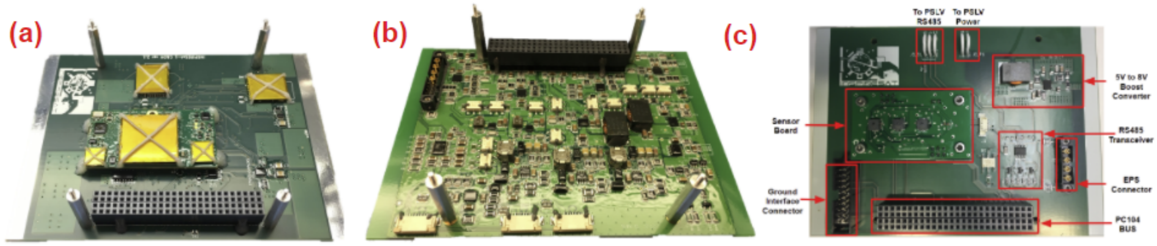

Figure 4: (a) IS0 CDH Board, (b)IS0 EPS Board, (c) IS-0 Adapter Board

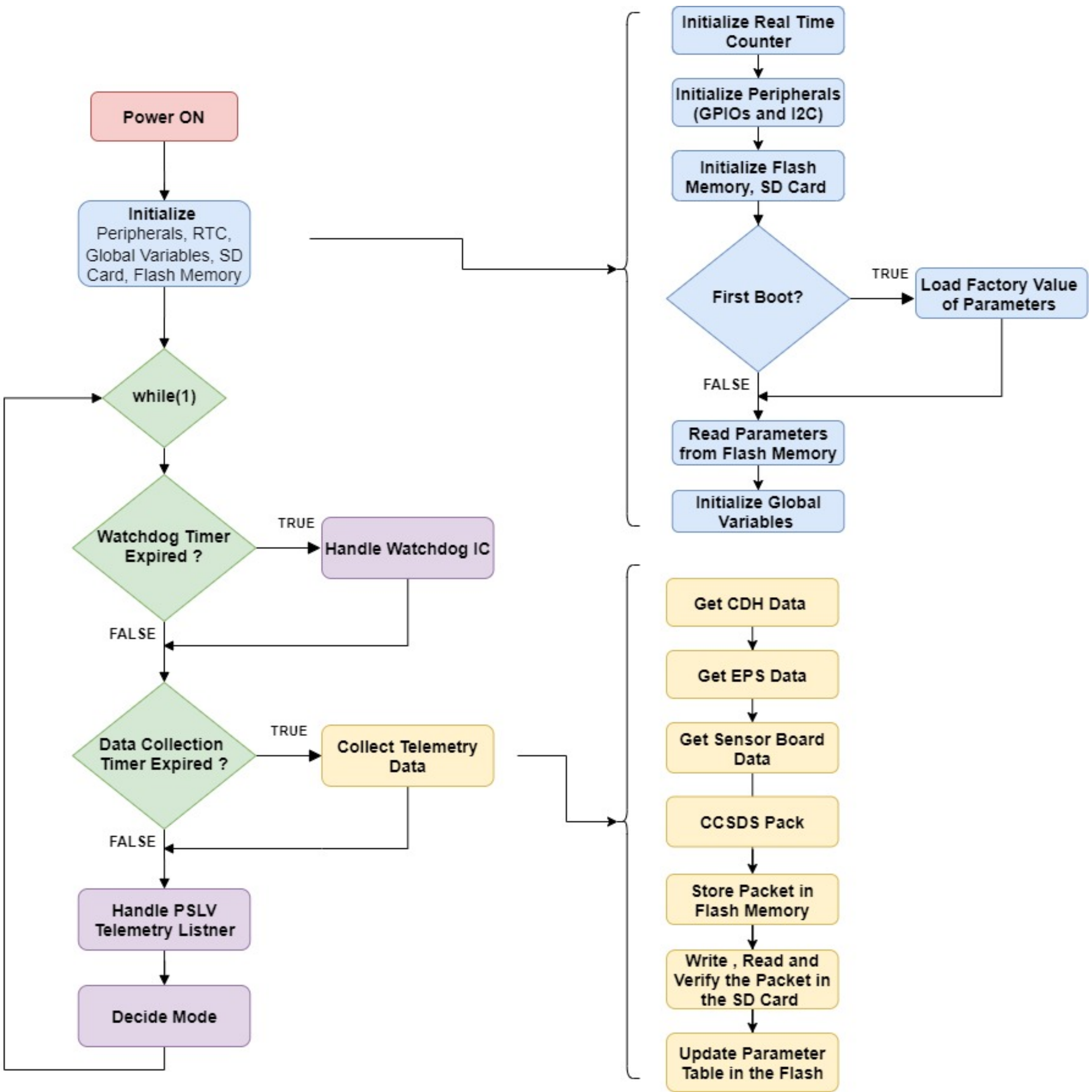

Figure 5: Flight Software Flowchart

parameters and variables. This is a one-time task that needs to happen only on boot-up.

After this, the program enters into an infinite while loop where the the tasks are carried out sequentially. First the external watchdog peripheral is handled, this is done by 'petting' the watchdog timer handler Verilog core with toggle signal every 1 second. This watchdog timer is used to generate a reset to the C&DH in case the flight software doesn't generate the toggle signal timely. Next, the data from the C&DH (which includes important flight software parameters), the EPS (voltage, current and temperature housekeeping data) and the PicoSIM sensor (the raw count values) board is collected using different peripherals. This data is converted it into the CCSDS beacon packet format and stored in the non-volatile flash memory of the SoM. The data packet is stored in the SD card and also read back from it to verify the working of the SD card. Once the packet is generated, the PS4-OP telemetry handler FPGA core's FIFO memory checked if it is empty/-full. If the FIFO is empty, a new packet is copied into the core's FIFO, so that it can be sent over the PS4-OP as required. The last task in the sequence of operations is to decide the mode of the flight software. In case of IS0 mission the mode switching is done on the basis of the Real Time Counter value, only for demonstration and testing of mode switching that will be useful for small satellite missions. In order to know that the flight software is able to execute all software tasks timely and robustly, long duration tests were conducted the details of which are described in the subsequent sections.

Structure and Mechanical Interface

The IS-0 payload consists of a single piece card cage with card rails to hold the PCB's in place. The sensor board is mounted to the interface board via standoffs. Two L-brackets are attached to the card cage. The payload can attach to the PS4-OP via the two L-brackets. The design of an additional base-board plate was also carried out, in-case the holes on the L-bracket cannot be used to mount the payload on the PS4-OP. The assembled payload is shown in the Fig. 6(a) with the mounting holes on the L-brackets marked in the bottom view. Analysis of the card cage indicates a Factor of Safety always above 15. The worst case results from the analysis with 15g in the X and Y directions is shown below (Fig. 6(b)). Left panel shows equivalent stress in Y Axis (top) and X Axis (bottom). Right panel shows total deformation in Y Axis (top) and X Axis (bottom). Modal analysis was also conducted for the payload that show the lowest frequency to be 227 Hz.

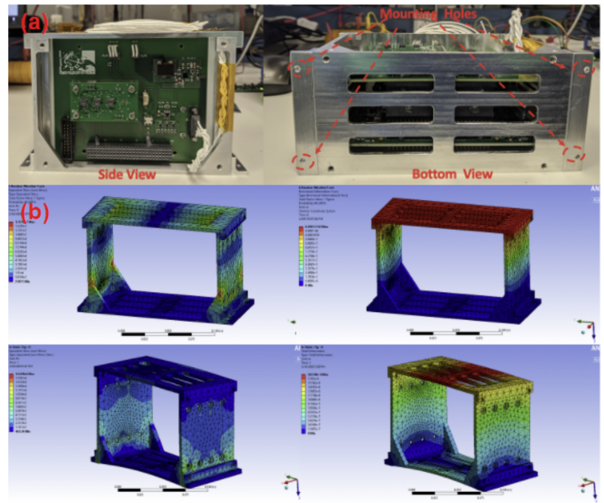

Figure 6: (a) IS-0 payload side views, (b) IS-0 structural simulation results

Testing and Analysis

Initially subsystem level tests were performed on each of the in-house developed boards. This was followed by interface tests to ensure proper implementation of the communication protocols between the boards. Tests were also performed on the PicoSIM sensor board to verify the gain linearity and the integration time linearity of the sensor. A white Mi-LED reference light was used and the raw sensor count(in all different wavelengths) was analysed for different gain and integration time settings of the sensor. As shown in Fig 7, these tests indicate that the both the gain and linearity have a proportionally linear effect on the sensor count and hence adjustments is not required for these parameters. Once the different subsystems were verified to be functioning properly, the subsystems were integrated. Performance tests were conducted on the integrated payload to verify the proper execution of the sequence of operations. Preliminary outdoor tests were also conducted on the payload to ensure that it is able to measure the solar spectrum.

Long Duration Testing

Multiple long duration tests were conducted on the payload to ensure robust functioning of the payload hardware and software. Data collected from the payload, including science and housekeeping data, was logged to a ground computer during the entire test duration. For example, four plots shown in Fig.

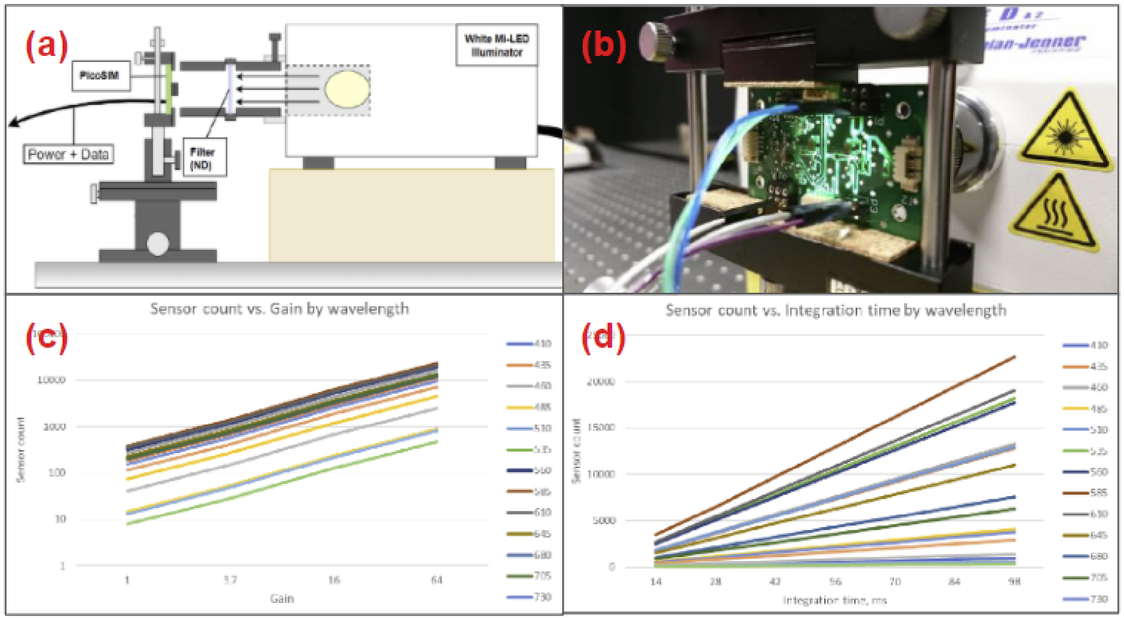

Figure 7: (a)Test setup block diagram, (b)PicoSIM testing setup, (c)Sensor Count vs Gain (d) Sensor Count vs Integration time

8 from a 16 hour long duration test. The Fig. 8(a) shows the time vs packet number in seconds. This time is obtained from the real time counter implemented on the FPGA. As the time is steadily increasing, it can be concluded that the RTC is functioning properly. Fig. 8(b) shows the SD card write-read-verify counter that indicates around 2,00,000 write and read-back cycles were conducted on the SD Card to verify proper functionality. Fig. 8(c) and (d) show the voltage and current of the C&DH board during the test duration.

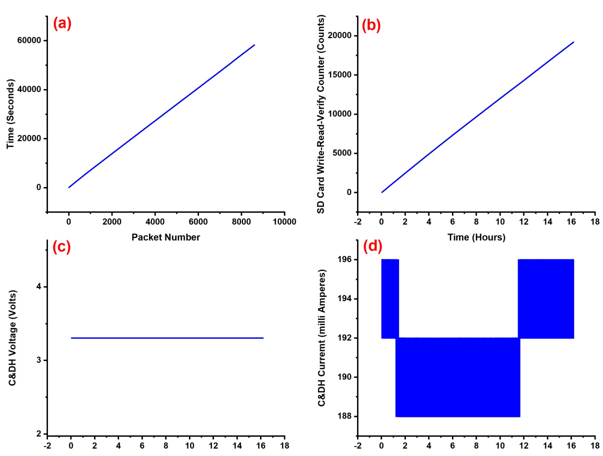

Figure 8: (a) RTC value (seconds), (b)SD card write-read-verify counter, (c) C&DH Voltage (d) C&DH Current

Environmental Testing

To ensure that the payload, which is primarily made out of commercial industrial grade components is able to survive space environment conditions the following measures were implemented during assembly. (1) To provide enhanced insulation and environmental protection of the PCBs (Printed Circuit Boards), a Urethane conformal coating was applied on the PCBs. (2) In order to ensure mechanical rigidity, some of the heavier components in the PCBs (for example the SoM on the OBC) were secured on the PCBs using a 3M Scotch-weld 2216 epoxy adhesive.

The thermal vacuum testing was conducted on the engineering model of the IS-0 payload at the TVAC chamber available at the Satellite Research Center at NTU. Environmental tests (Vibration testing and Thermal Vacuum testing) were also carried on the flight model of On-Board Computer Board and the Electrical Power System board as a part of the integrated INSPIRESat-1 small satellite. Similar environmental tests were also carried out on IDEASat (which is the second INSPIRE small satellite mission), which contains a modified version of the C&DH and EPS board.[12] The results from these tests show proper functionality of the EM payload in space environment conditions, similar tests on the flight model will be carried out at a later stage.

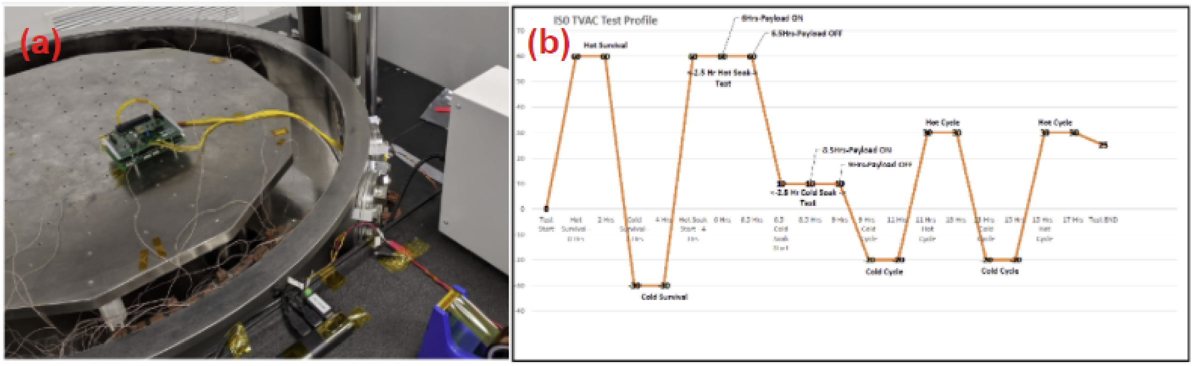

Figure 9: (a) IS0 EM TVAC testing Setup, (b) TVAC Test Profile

Conclusion

The IS-0 payload was developed with a goal of characterizing the solar spectral irradiance using a novel compact sensor. The integrated payload development was completed and preliminary environmental tests were successfully conducted on the engineering model of the payload. The flight model of the payload was also developed and comprehensive performance tests were completed to ensure proper functioning. The environmental tests on the flight model of the payload are planned for the third quarter of 2021.

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