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i-INSPIRE --- AUSTRALIA'S FIRST UNIVERSITY PICO-SATELLITE MISSION

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ABSTRACT

The i-INSPIRE (initial - INtegrated SPectrograph, Imager and Radiation Explorer) satellite will be the first satellite from an Australian University to be designed, built by postgraduate student, and actually launched and operated in space. Scheduled for launch in 2013, i-INSPIRE will carry a novel photonics-based spectrograph, an imaging camera, and a miniaturized radiation detector. The satellite and instruments (except the imaging camera) are designed and built at the University of Sydney.

The satellite body is cylindrical with a 9 cm diameter and 13 cm height. Since it has a tubular shape, this satellite is also called a TubeSat. Satellite platform distributes the power, communication and on board data handling (OBDH) subsystems into three individual PCBs (Printed Circuit Board). As the key of whole system, OBDH subsystem consists of one low power consumption MSP430 microcontroller for main data processing and hardware TNC (Terminal Node Controller) for communication under AX.25 protocol. As i-INSPIRE is a pico-satellite with a mass less than 1 kg, it's a great challenge to fit real scientific instruments. The fundamentally new device, Nanospec (Nano-Spectrograph), has the potential to have world-leading wavelength resolution and diffraction-limited rather than the typical size in modern astronomy. The radiation detector is a small Geiger counter that detects the number of energetic electrons, protons, and other "cosmic rays'' passing through the detector. The imaging camera is an off-the-shelf device. The total cost of the satellite and instruments, including test versions, is less than $10,000, and the i-INSPIRE project will be a prototype for future larger and more complex missions.

I. INTRODUCTION

As being developed, i-INSPIRE satellite has scientific, technical and strategic aims. The main scientific aims are as follows. Firstly the operation in space of a newly-designed photonic (i.e. optical fibre fed) micro-spectrograph called NanoSpec. This will be the first compact high-resolution photonic spectrograph from Australian universities to be operated in space. The unique radiation environment of space also enables us to probe the radiation environment in Low Earth orbit by our customized Geiger counter. Imaging camera is added in design for the reason that not only can it undertake earth observation but also coarse indication of attitude.

The secondary subjective is the "tube" structure can be drawn on for other types of pico-satellite design. Current subsystems maintain the partial design of the TubeSat prototype from IOS (Interorbital Systems Corporation). The kernel of all subsystems—one on board computer based on MSP430 microcontroller—is dedicated design for our mission. The AFSK based UHF communication implementation cooperating with our newly-built ground station will be the meaningful technical storage for similar project ahead. Furthermore, the present on-board working mechanism paves the way for more complex housekeeping software used in future mission.

i-INSPIRE satellite is a part of launch package with IOS, which is one of 32 TubeSats and 10 CubeSats currently on the manifest for the maiden launch of IOS's N45 rocket [2]. The targeted orbit is a high inclination polar orbit with an altitude of 310 km and a predicted life time of ~24 days. During the life time, we expect to observe cosmic radiation particles by our devices. The data from the radiation counter will be correlated with data from NanoSpec as we expect to see increased contamination of spectra from Cerenkov radiation when i-INSPIRE traverses areas of higher radiation intensity.

II. REQUIREMENT

Our scientific objectives, i-INSPIRE design specification, the launch and orbital environments establish the design requirements for the electronic systems of satellite. These requirements include:

a. Mechanical structure

b. Electronic device and payload

c. Communication method

d. Space environment

II.1 MECHANICAL STRUCTURE

Fundamentally, mechanical design of i-INSPIRE should comply with the TubeSat standard from IOS, while IOS does not issue any regulations regarding the electrical specification. Its structure that distributed subsystems on separate PCBs and arrangement of internal space has been demonstrated in the TubeSat prototype.

This 0.75Kg tube-shaped structure is defined with a height and diameter of approximately 130 mm and 90 mm respectively [2]. As shown in Fig.1, the exterior of the satellite is covered by vertical aluminium strips and solar panels. The two elements of the antenna are secured to the top of the satellite, with a tip-to-tip length of 330 mm. The three small, white cylinders on each end of the satellite are bearings made of Teflon which help to slide satellite out of its ejection tube into space [2]. Ejection is achieved by spring-driven ejection. The two elements of the centre fed half wave dipole antenna on the top are made from spring steel, allowing them to be bent when packing satellite in the ejection tube.

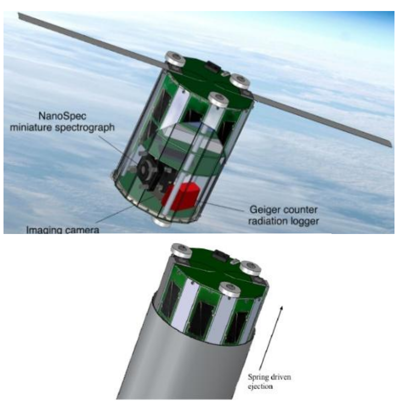

Fig. 1: Simulated image of the i-INSPIRE satellite and packing of i-INSPIRE inside the ejection tube

Considering the mass margin of 1Kg, i-INSPIRE gives priority to electronics and payloads as much as possible. Currently, the one third mass and volume budget is arranged for scientific device, in the mean time, each subsystem PCB is controlled no more than 50g.

CATEGORY	MASS
Mechanical Structure	140g
Battery and solar cells	180g
Antenna	30g
Subsystems PCB	150g
Nano-spectrograph	206g
Geiger counter	40g
Camera	20g
Total mass: 766g	

Table 1: Mass budget of i-INSPIRE

II.2 ELECTRONIC DEVICE AND PAYLOAD

Since i-INSPIRE will fulfill relatively complex physical observation, collected diagram and data are necessary to be stored in on-board memory. Current payloads apply COTS (Commercial Off the Shelf) sensors from diverse manufacturers, which means it is hard to use single data bus standard. Therefore, on-board computer should be capable to provide various interfaces. To guarantee the enough power supply during the life time of i-INSPIRE, power subsystem need to be competent to satisfy the power consumption of whole system. One power budget based on the power management (PM) subsystem from IOS has been made as shown in Table 2. According to this table, this PM subsystem is considered qualified for our planned mission.

Subsystem	Power (mW)	Duty cycle (hrs/day)	mWh/day
Power	558	19.4	10852
Onboard data handling	150	24	-3840
Transmitting	110~600	12	-2000
Receiving	27	12	324
Payloads	55	24	-1320
Total Energy Available (mWh): 10852			
Total Used (mWh):7484			
Energy remaining (mWh)：3368			

Table 2: Power budget of i-INSPIRE

II.3 COMMUNICATION METHOD

For most pico-satellite missions, amateur radio equipment and frequency would be the best selection for the consideration about cost, availability etc. Basically, the telemetry data is expected to be easily received by radio amateurs on amateur radio frequencies. As regarding to specifics of communication system, the essential requirement for downlink and uplink is having enough EIRP (Effective Isotropic Radiated Power) when transmitting occurring. According to the link budget of our ground station in the University of Sydeny, transceiver and amplifier used in TubeSat prototype had been considered appropriate and kept in our mission.

II.4 SPACE ENVIRONMENT

All the spacecrafts have to face the harsh orbital environmental and strong vibration during the launch. In this case, space grade components are the best choices to endure all these impacts. However, for one pico-satellite project limited by cost budget and development time, it's unlikely to utilize expensive space grade components which are originally developed for commercial or military spacecraft. Nevertheless, we still hope to assure the reliability of i-INSPIRE satellite when using COTS components. As planned, the prototype of i-INSPIRE should pass the high altitude balloon test, thermal-vacuum test, vibration test and radiation test respectively.

III. SATELLITE BUS

As a first pico-satellite of Australian universities to be launched, our effort is mainly on completing scientific observation tasks and increasing reliability of i-INSPIRE. For the one hand, mature technical methods are applied in current design which is expected to be the cornerstone for future complex missions. On the other hand, we aim to obtain more meaningful scientific data based on one reliable bus, rather than primarily testing satellite bus itself with few payloads as done by most small satellites in their first mission. In i-INSPIRE design, all the subsystems will work around the three payload devices.

As shown in Fig.2, a pair of dipole antenna is soldered on the top board and scientific payloads are located on the bottom layer within the TubeSat. In the middle of the frame, power management, communication, and OBDH subsystems are distributed onto the three remaining PCBs. As the core of the whole system, the OBDH board will control the peripheral components while storing and retrieving data. In addition, one low power consumption IMU is added to provide satellite body attitude information which could be helpful for the scientific observation records.

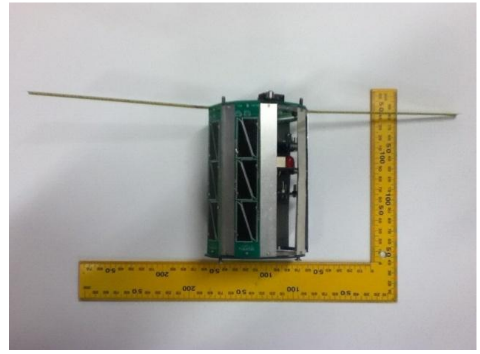

Fig. 2: A photograph of the i-INSPIRE satellite body

III.1 ON BOARD COMPUTER (OBC)

The designed OBC mainly consists of three microcontrollers which are responsible for operating other subsystems. For the central controller, i-INSPIRE applies one MSP430F5438 microcontroller from Texas Instruments. This model is appropriate for our mission as it has relatively large RAM (16KB), affluent on-chip hardware resources like RTC (Real Time Clock), thermal sensor, affluent interfaces(SPI, I2C, UART) [4]. Based on these merits, we are able to access the COTS components with different data bus protocol.

Fig.3: On Board Computer PCB photograph. It is clear to see the MSP430 MCU on red sub-PCB and two PIC controllers in parallel

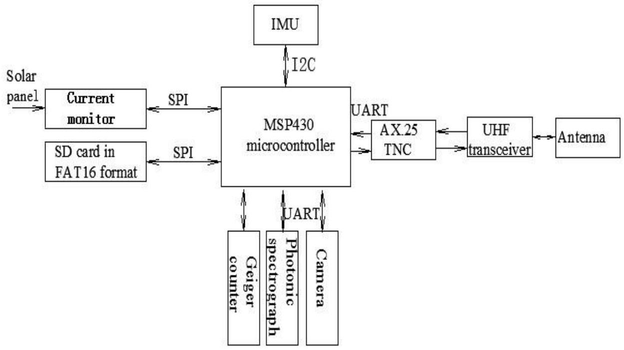

Fig.4: Architecture of i-INSPIRE hardware

There are other two PIC microcontrollers [5] from Microchip mounted on OBC and playing the role of TNC (Terminal Node Controller). Since during the downlink and uplink AX.25 framing is used to send data packet, one decoding & encoding device is essential. It is worthy to be mentioned that hardware TNC is chosen here but not software, although one version of OBC with software TNC had been designed. Software TNC actually can simplify the circuit, meanwhile, increasing the complexity of software on MSP430. Hence, hardware is deemed to be more robust. Moreover, it will reduce the computational complexity of the CPU and enable it to focus on high level functions.

In terms of the size of payloads data, it is hard to store them in the RAM or ROM of one microcontroller because both NanoSpec and camera output the JPEG diagram with relatively high resolution of 640*480. In this case, one SD card with FAT16 file system is adopted to store data. Real-time stamps will be added to the scientific instrument.

The behaviour of the OBDH subsystem is governed by housekeeping software which implemented by our MSP430. In this state machine, as shown in Fig. 6, after successful initialization, the controller will start collecting observation data from payloads, then establish the link with ground station and complete data transmitting. Additionally, watchdog in software is applied to guarantee system robustness.

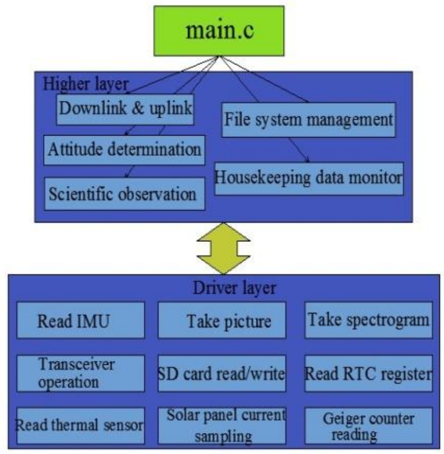

Fig.5: Hierarchical structure of housekeeping software

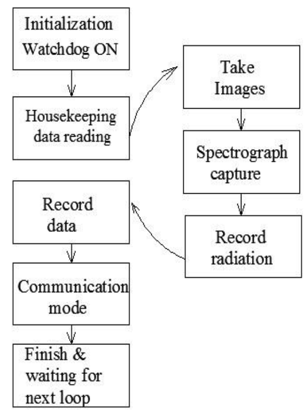

Fig.6: Operation flow char of i-INSPIRE

III.2 COMMUNICATION SUBSYSTEM

This subsystem is for transmitting and receiving the signals and so must be able to switch from transmitter mode to receiver mode. Thus, different frequency can be selected according to three address pins on transceiver. In order to ensure the power of the transmitting signal is large enough to be received on Earth, an amplifier is used to increase the power of the signal. The current design uses a TR2M transceiver, which works in the amateur radio frequency range of 433-434 MHz, at a power of 100 mW. A 500mW RF amplifier AFS2 is used to extend the operating range. The TR2M and AFS2 with relevant power regulator take up one independent PCB as Communication subsystem.

In order to obtain efficient data link, all the data in the uplink and downlink will be encoded into AX.25 protocol packets and then transmitted with AFSK modulation at a 1200 baud rate. During the transmission mode, the MSP430 will directly send data to encoder via UART interface and then transmitted by transceiver. In receiving mode, when telemetry command is available from decoder, MSP430 will enter into interrupt service routine to pick up. The telemetry command will be verified to make the next move.

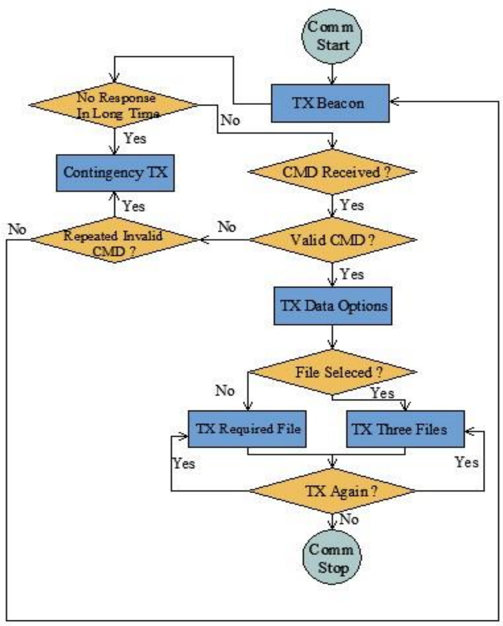

Fig.7: State machine of communication mode

The communication subsystem will work as one state machine as well. It is described in Fig.7. When the satellite's main program enters communication mode, AX.25 beacons will be transmitted at fixed intervals while the satellite is waiting for the ground station's response. Beacon signal may involve on-board temperature, attitude information, on-board real time and current condition of solar cells. When the telemetry command is confirmed, i-INSPIRE will transmit data via the transceiver in AX.25 packet format. Additionally, one mechanism has been built in that once i-INSPIRE receiving too many invalid commands or having no response from ground station for a long time, it will send one group of data "blindly". In the end, after sending needed data, communication mode will be terminated and then the system will return to housekeeping program.

III.3 POWER MANAGEMENT SUBSYSTEM

Both COMS and TTL components are applied on i-INSPIRE that means corresponding voltage convertors are needed. On OBC board and transceiver board, separate 5V and 3.3V LDO (low dropout voltage) converters are responsible for supplying proper voltages. We maintain the two-stage power management circuit design from IOS. The first stage contains one LDO linear regulator LT3021, which will collect power from 8-channel solar panels and feed the second stage and battery with constant 4.2V voltage. For most LDO converters, they require input voltage should be higher than typical output. Therefore, the second stage mainly includes one boost converter, which improves the 4.2V input to 5.7V that is provided to each subsystem.

In each solar panel channel, current-sense amplifier is used to monitor the output condition of single solar panel. The analogous output of eight current-sense amplifiers will converge at one 8-channel AD convertor MAX1112. This convertor enables MSP430 to read the current condition on every solar panel via SPI interface.

For energy storage, Li-ion battery is selected for its high volumetric and gravimetric energy densities. Current design uses one Li-ion battery whose nominal capacity is 5500mAh with 3.7V voltage. This battery is placed in the middle of PM PCB.

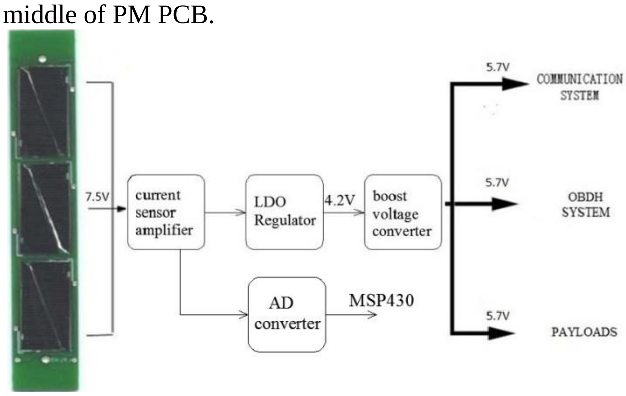

Fig.8: Structure of power management subsystem

In Fig.8, it depicts the principle of operation of PM subsystem. Solar panels convert the solar energy to the electrical energy, with typical output of 7.5V per panel. Original voltage from parallel solar panels passes through the LDO regulator and reduced to 4.2V, which is proper voltage for battery charging. And then, boost voltage converter will step up the power to 5.7V to feed other subsystems.

IV. PAYLOADS

i-INSPIRE carries three instruments in its science payloads which are located at the bottom and fully utilize the limited payload space. These are a novel photonic nano-spectrograph, a Geiger tube radiation counter, and an imaging camera. As shown in following figure, one 3D diagram describes the mounting type of NanoSpec and camera.

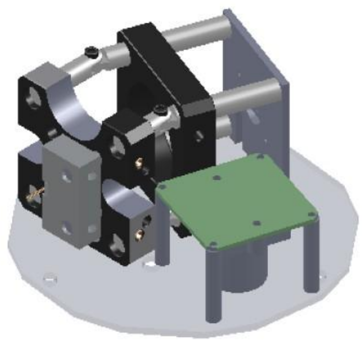

Fig.9: Proposed layout of NanoSpec and camera

IV.1 NANOSPEC

The goal of NanoSpec is to demonstrate the potential of photonics-driven technology in space-based applications. To that end we have designed and built a photonic spectrograph, specifically a single mode fibre-fed diffraction limited device, which will survive a launch into space while still providing respectable spectral resolution. The spectrograph design is based upon the PIMMS5 concept [1].

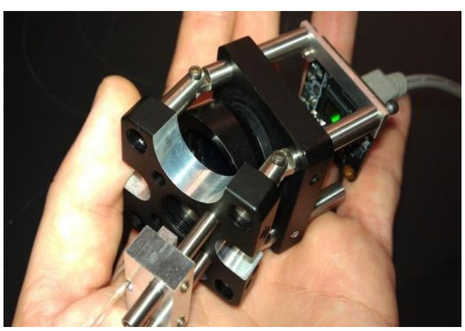

Fig.10: A photo of NanoSpec prototype

NanoSpec is compatible with a photonic lantern input. However the final flight instrument will not include one. Instead, NanoSpec's single mode input fibres will be arranged in pairs pointing in opposite directions out the sides of the i-INSPIRE, as illustrated by the red and blue lines in Fig. 4b. The eight fibres are split into four pairs with one of each type in each pair. This arrangement is designed to ensure that no matter the orientation the spacecraft, a spectrum will be generated by either the Earth, Sun, Moon or other astronomical sources. Additionally, the pairs consist of two different types of fibre in order to test their performance in the LEO environment.

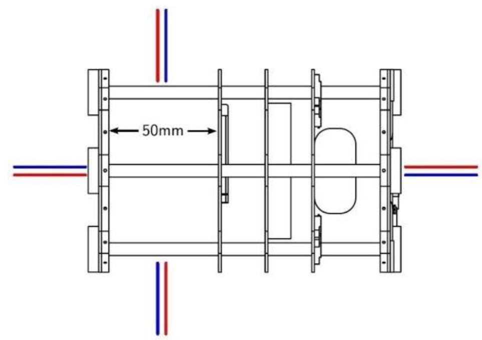

Fig.11: Fibres arrangement in a side view i-INSPIRE

IV.2 GEITER COUNTER

i-INSPIRE also carries a Geiger－Müller counter. This counter is designed to count the Cerenkov flashes, drawing a radiation map to have a survey of the radiation in the orbit. The counter's pulses of output are recorded by MSP430 and saved into SD card with time stamp. This device is expected to be opened during the whole life time, and record pulse number as a file every ten minutes. In Fig.13, it shows one replotted pulse from our Geiger counter which originally captured by scope.

Fig.12: Designed mini Geiger counter

Initially, we planned to directly use the Geiger counter of commercial version from Sparkfun. However its length is more than 10cm so that not suitable for our mechanical structure. In this situation, we designed our own Geiger counter that dramatically reduces the size by using miniaturized DC-DC transformer and small Geiger tube detector. On the other hand, the drawback of miniaturization should be clarified that we pay the decline of detector sensitivity as the cost. The sensitivity is depending on the volume of the tube, or the pressure of the gas filled in tube [3], and the voltage as well. A bigger Geiger tube with higher voltage is more likely to generate a pulse when a particle goes through. Taking everything into account, this miniaturized design is not perfect for its performance but maybe the appropriate one for our mission.

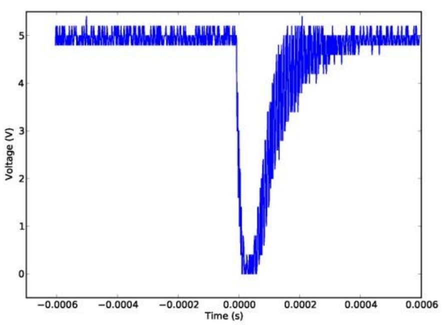

Fig.13: Output pulse of Geiger counter

IV.3 CAMERA:

The imaging camera is designed and built by LinkSprite for hobbyist community. It was chosen for two reasons: Firstly it is controlled over a TTL level serial interface allowing for simple integration with the i-INPSIRE micro-controller; secondly it has built in JPEG compression allowing for higher resolution images in the data budget. The primary goal of the imager is to obtain images of the Earth from orbit. We also believe that a series of images taken at regular intervals will allow us to determine an approximate attitude of the spacecraft, in case of inertial measurement unit (IMU) failure. As i-INSPIRE does not have any attitude control, we cannot control where it is pointing while in orbit. The imager will take images at regular intervals (that are out of phase with the predicted pith of the tumble), ensure that an image of the Earth is taken.

Fig.14: Photo of imaging camera

IV.4 IMU:

This COTS IMU shown in Fig.15 is added as last member of payloads. Due to the limited power budget, no attitude control method exists in current i-INSPIRE design. However, it’s advisable to introduce one MEMS (Micro-electromechanical Systems) IMU whose size is not bigger than 3.5cm*1cm to provide real-time attitude. The attitude information, which may be added in the end of each file as attitude stamp, could be significant for the future analysis of scientific data.

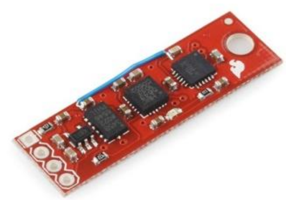

Fig.15: IMU stick from Sparkun

This IMU from Sparkfun integrates three MEMS sensors: accelerometer, magnetometer and gyroscope. The Kalman filter method has been developed and implemented on our MSP430 for the aim of sensor data fusion. In addition, due to the absence of GPS, a lookup table of magnetic field will be needed when making magnetic readings.

V. TEST

The pre-launch tests for i-INSPIRE will aim to test the satellite under conditions more extreme than those expected during launch and in space. As planned, all subsystems and payloads have undergone lab-based testing to confirm that they operate to the specifications we require.

V.1 Flat-Sat test

The flat-sat test means the whole i-INSPIRE without mechanical structure tested under lab conditions. All PCBs from different subsystems in cable connection construct the flat-sat. This test would be the fundamental simulation to operate whole system and verify the software design for all devices.

The procedure of test is fulfilled according to the flowchart Fig.16. One interface of ground station is shown in Fig.17, after the telemetry command confirmed by i-INSPIRE, it will transmit data continuously and then terminate this downlink if feedback obtain or time out occurring.

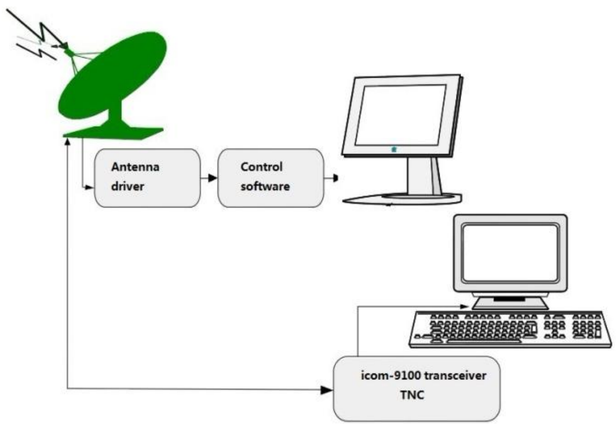

Fig.16: Ground station structure used in test flat-sat test

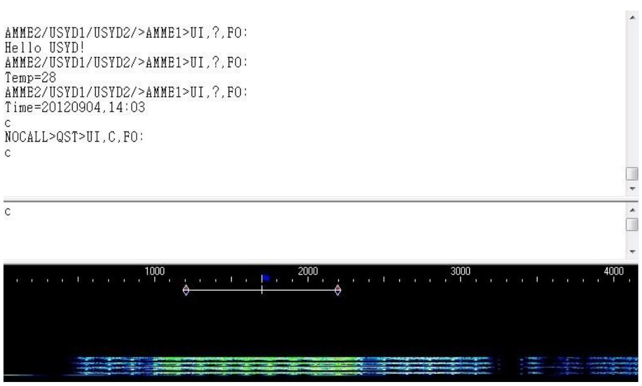

Fig.17: Screenshot from software TNC on ground station. Beacon signal involving temperature and time from i-INSPIRE can be seen and ground station send "c" which means confirmation as telemetry command.

The sensors of NanoSpec and camera have compressed the captured diagram into JPEG format before output to MSP430, at the same time, each file from the sensor includes additional framing bytes like attitude information or time stamp that 'surrounds' the JPEG file. These additional bytes must be removed to leave a valid JPEG file that may be recognised and opened by a PC. In Fig.18, shows the recovered diagram received by ground station during the test. And Fig.19 is the received spectrogram.

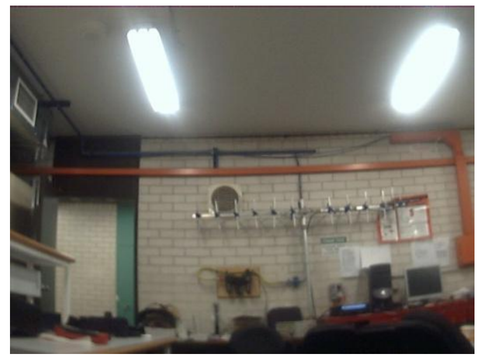

Fig.18 Picture taken in lab

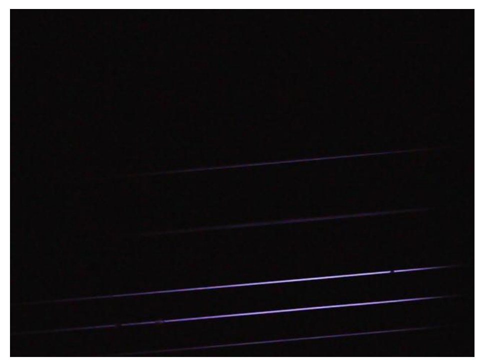

Fig.19 Spectrogram taken by NanoSpec under natural light

V.2 Balloon test

To test i-INSPIRE in one relatively harsh environment, one high altitude balloon will carry i-INSPIRE and flying on a height of about 20km. This balloon launch will take place on September, in Adelaide, Australia. The low temperature and long communication distance are totally different from the condition in lab. Therefore, it would be the practical and comprehensive test for all subsystems.

V.3 Other test

Besides, tests comprise a thermal vacuum test, a radiation test and a vibration test in the future. The thermal vacuum test will examine the robustness of the entire satellite to temperature variations likely to be encountered by i-INSPIRE as it moves in and out of the shadow of the Earth. The entire satellite will be placed in a vacuum chamber while the thermal cycles are applied. The range of temperature variations and timescale used will be similar to those expected in space.

For the radiation test i-INSPIRE will be exposed to a radiation field roughly twice that expected in space. We are critically interested in whether this causes any damage to the electronic components of the satellite, so this test will be performed while the satellite is operational. This will allow us to monitor the effect on the imaging camera and NanoSpec's detector in real-time. The vibration test is a mechanical test designed to mimic a space launch. The vibrations which i-INSPIRE will endure during launch will be recreated by a vibration platform to which the satellite will be attached.

VI. CONCLUSIONS

In this paper, the scientific observation mission, which to be carried out by i-INSPIRE satellite, has been given the detailed introduction. Although i-INSPIRE is classified as the pico-satellite, our people from University of Sydney schedule the mass budget in a reasonable way and exploit the limited on-board space to the full. As the most innovative point of i-INSPIRE, three dedicated scientific devices are neatly placed in one $300cm^3$ space and play various role in probe the space environment, especially, the radiation environment.

To guarantee the proper operation of payloads, subsystems hardware is customized drawing on the TubeSat structure from IOS. We developed the software from housekeeping program to all devices driver based on practical mission requirement.

The satellite will be launched in late 2012 or early 2013 when rocket from IOS is ready. Before the real launch, we meticulously carry out a series of tests for design verification. So far we have obtained satisfying result in lab condition and further test like balloon launch is in progress.

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