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INSPIRESat-1 Nanosat MissionAnkit Verma¹, Yi Duann², Spencer Boyajian³¹Indian Institute of Space Science and Technology, ²National Central University, ³University of Colorado Boulder
Indian Institute of Space Science and Technology, Valiyamala, Thiruvananthapuram, Kerala, India.¹ ankit.sc15b075@ug.iist.ac.in, ² cntwtpe@gmail.com, ³ Spencer.Boyajian@lasp.colorado.edu**Faculty Advisor:** Amal Chandran³, Priyadarshan¹, Loren Chang²¹Indian Institute of Space Science and Technology, ²National Central University, ³University of Colorado Boulder**ABSTRACT**

The INSPIRE, International Satellite Program in Research and Education, is a group of six institutes namely Laboratory for Atmospheric and Space Physics (LASP), USA, Indian Institute of Space Science and Technology (IIST), India, National Central University (NCU), Taiwan, Nanyang Technological University (NTU), Singapore, Sultan Qaboos University, Oman, Le Laboratoire Atmosphères, Milieux, Observations Spatiales (LATMOS), France. Three institutions LASP, IIST and NCU are developing the first satellite of the program called the INSPIRESat-1, whose mission details and design are presented in this paper. The paper gives the details of payload, its mode of operations and its interface with other subsystems, Command and Data Handling (C&DH) system and its capabilities, Electrical Power Supply (EPS) subsystem, access and power analysis, and modes of operation. It also describes Flight Software (FSW), communication, Attitude Determination and Control System (ADCS), and structures.

INTRODUCTION

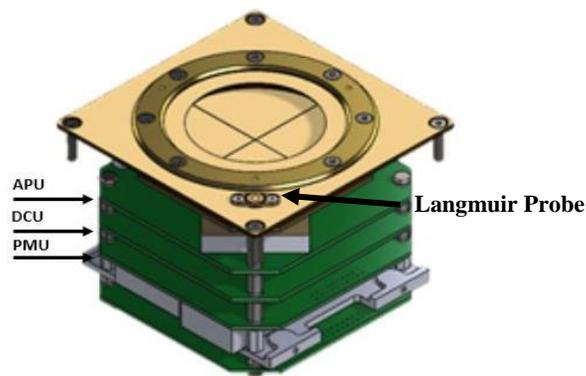
The International Satellite Program in Research and Education's first satellite (INSPIRESat-1) is a custom built nanosatellite weighing ~ 8.5 kg with dimensions of 290x200x160 mm (~ 9U), slated for launch in late 2019. It is aimed to study ionosphere, its ion composition, plasma densities, ion velocities, and ion temperature. The focus of data collection is on eclipse time and the transition time from sunlight to eclipse time. The design, realization, and operation of the INSPIRESat-1 aims to combine the expertise of the participating institutions to enable science and give real-world engineering experience to student participants. The INSPIRESat-1 spacecraft contains the inhouse developed Compact Ionosphere Probe (CIP) as the payload, C&DH, developed EPS, off the shelf Blue Canyon Technology's (BCT) XACT as ADCS, Spacequest's TRXU UHF transceiver, and Cape Peninsula University of Technology's STX as SBand transmitter. The student developed C&DH and EPS systems are expected to be utilized in the future satellites developed by the INSPIRE program.

PAYLOAD

The Compact Ionosphere Probe (CIP), developed by Space Payload Laboratory at NCU, was selected as a science payload in the 1st International Satellite Program in Research and Education (INSPIRE) Workshop held at NCU in 2016. The CIP, a successor of Advanced Ionospheric Probe¹, is an all-in-one

plasma sensor that uses a single instrument to perform multiple sensor functions in a time-sharing mechanism.

The CIP performs in-situ measurements of the ionospheric plasma compositions, ion concentrations, velocities, and temperatures to explore the terrestrial ionosphere.

**Figure 1: CIP mechanical structure**

The CIP contains three circuit boards:

1. Analog Preprocessing Unit (APU): It transduces currents from sensor into digital signals.
2. Digital Control Unit (DCU): It controls digital to analog/analog to digital converters (DA/ADs) on APU board, monitors PCBs' temperature, and

receives commands/sends science data from/to C&DH.

- Power Management Unit (PMU): It supplies and regulates necessary powers for CIP.

Table 1: Preliminary CIP specifications

Parameters	Value
Mass	0.5 Kg (< 1 Kg)
Dimension	0.7 U
Voltage	12 V
Power	3.45 W
Interface	UART, 115200 bps (RS422)
Connector	9-pin D-sub female.

The data is transmitted using UART with RS422 encoding. The C&DH transmits commands to the CIP at $115,200 \pm 1\%$ baud, with 1 start bit, 8 data bits, and one stop bit.

Modes of Operation

CIP has the following operation modes:

- Planar Langmuir Probe (PLP): Measures electron temperature (T_e).
- Ion Drift Meter (IDM)/Ion Trap (IT): Provides arrival angles (θ_v and θ_H) of ion velocity (V_i) and ion density (N_i).
- Retarding Potential Analyzer (RPA): Measures ion temperature (T_i), ion composition (C_i), ion density (N_i) and ion ram velocity (U_r).

Each mode can either be in *normal mode* or *fast mode*. There is 1 data packet available every second in *normal mode* and 8 every second in *fast mode*.

The C&DH formats CIP commands into 8 bytes consisting of 2 header bytes, 1 function code byte, 4 data bytes (time tag or command), and a checksum byte computed using 3rd through the 7th command bytes. The CIP will reject commands with bad framing or checksum. The C&DH sends all commands to the CIP within the 900 ms interval of one of the one second (1PPS) pulses, as shown below:



Figure 2: Command synchronization with the PPS signal.

Two kinds of science data packets are available. One is the raw science data packet (280 bytes) and the other is processed science data packet (60 bytes). The CIP raw science data packets are 280 bytes long. Each packet shall start with a 23-byte header that consist of a 2 start bytes, 1 function code byte, 4-byte data time tag, and 16-byte status of health (SOH) data. The header will be followed by 256-bytes of CIP science data. The data will be followed by one footer byte checksum. The checksum byte shall be constructed using the 3rd byte through the 279th byte of this data packet. The processed science data consists of 23 bytes header, 36 bytes of science data (processed) and 1 bytes of checksum constructed using the 3rd byte through the 59th byte.

CIP shall transmit all data packets within the period starting at the leading edge of the C&DH PPS signal and ending at least one-half period before the following PPS.

MISSION DESIGN

The aim of the mission is to study ionosphere, its ion composition, plasma densities, ion velocities, and ion temperature at mid altitude regions. Beside the scientific aim, the goal of the mission is to develop a nanosatellite by collaboration among different institutes all around the world. The mission statement is as follows:

Improve the understanding of Ionosphere dynamics through observations of ion temperature, composition, density and velocity.

Orbit Details

To make mid-latitude nighttime ionosphere measurements to study ionospheric effects of *mid night temperature maxima* and night time Ionospheric plasma bubbles, INSPIRESat -1 desired orbit requirements are:

- Altitude: 500 ± 50 km
- Inclination: $55^\circ \pm 10^\circ$

This gives us orbital period of ~ 95 minutes with 35 minute average eclipse times.

Design

To meet the mission requirements each subsystem has either been self developed or commercially procured. Following are the details of each subsystem:

Table 2: Subsystem and responsible institute

Subsystem	Short Description	Institute

Payload	Compact Ionosphere Payload (CIP)	NCU
C&DH	Self - developed	IIST
Power	Self - developed	IIST, NCU
Structure and Thermals	Self - developed	LASP
ADCS	XACT, Blue Canyon Technology	LASP
Communication	Space Quest, Clyde Space	NCU

BCT XACT is highly capable ADCS system. Power subsystem is designed to provide stable and adequate power to all subsystems. Communication subsystem incorporates UHF transceiver and S-Band Transmitter, C&DH has been developed to incorporate all the interfaces and controlling them and data storage of at least 3 months. Structure has been developed based on ISRO launch loads, strong enough to survive launch and space environments.

For interconnection between subsystems standard PC104 is used. The commercial off the shelf components have a D/micro-D type connector that is re-routed to PC104 connectors through an interface card. The following image shows the placement of each subsystem in the structure:

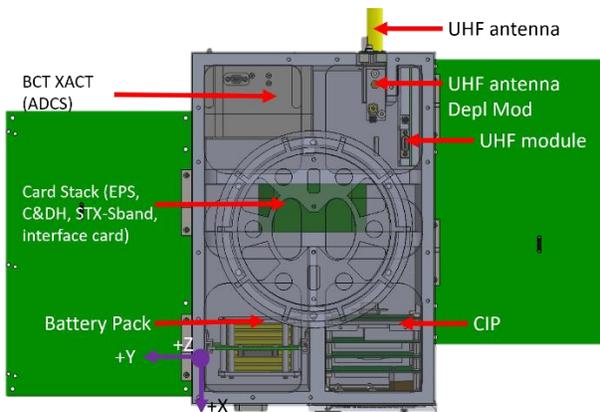


Figure 3: INSPIRESat-1 internal structure and Co-ordinate axis

Analysis

Access Time and Downlink

The following graph shows the access time for the three ground stations of INSPIRESat-1.

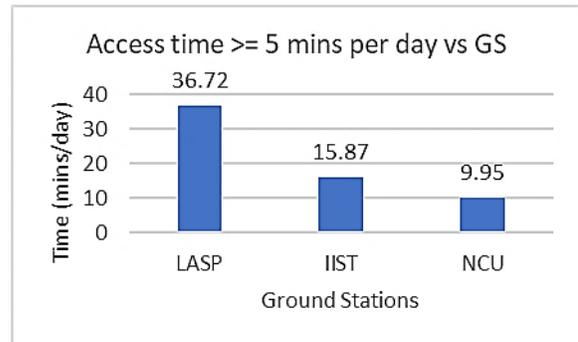


Figure 4: Access time

The data is downlinked over SBand frequency to LASP, the uplink is over UHF. Other ground stations will use UHF for uplink and downlink of essential HK data.

Table 3: Downlink data per day

UHF Data rate	19.2 kbps	SBand data rate	0.25 MBps
GS	Access time per day	UHF data (MB/day)	SBand Data (MB/Day)
LASP	36.72	-	550.80
IIST	15.87	2.23	-
NCU	9.85	1.40	-
Total	62.54	3.63	550.80

Power Analysis

The power analysis has been done to find out the power generation and hence prepare a power budget. The concept of the power analysis is as follows:

1. Satellite's +X (Figure 3) points in direction of velocity during eclipse time for payload to take reading.
2. Satellite's solar panels point in sun direction during sunlit period.
3. A buffer of 5 minutes is provided for satellite at the start and end of eclipse period to switch from RAM orientation to sun pointing, during this time sunlight falls at an angle on the solar panels, which is obtained from System Took Kit (STK).
4. Solar panels absorb the energy from sunrays falling on them with efficiency of 26.6% at 65° C (worst case).
5. Buck converters driven by Pulse Width Modulation signal from C&DH transfer the energy to power bus.
6. Satellite does not produce any power during SBand transmission, as SBand patch antenna is on the same face as body-mounted solar panels

which points toward nadir direction during transmission.

Following are the worst-case inputs:

1. No. of solar cells: 26
2. Area of each cell: 30.84 cm²
3. Efficiency of solar cell (at 65° C): 26.6%
4. Buck converter efficiency: 80%

The analysis of power generation has been done in the time interval of 1 year, from September 1, 2019 to September 1, 2020.

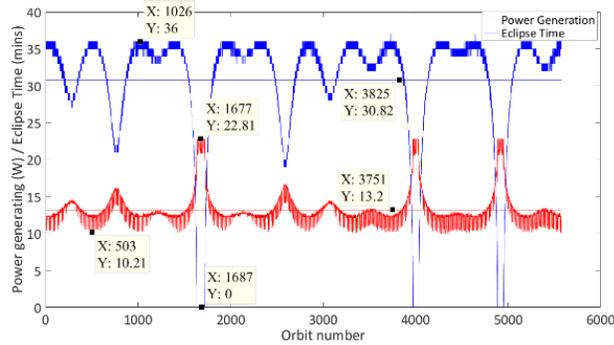


Figure 5: Power Generation over 1 year

The average power generated = 13.20 W. The power budget has been made based on average power consumption in an orbit by all the subsystems.

Table 4: Power Budget

Subsystem	Peak Power (W)	Nominal Power (W)	Duty Cycle (%)	Average Peak power (W)	Average Nominal power (W)
C&DH	1.40	0.91	100	1.40	0.91
Power	1.78	1.78	100	1.78	1.78
ADCS	2.82	2.82	100	2.82	2.82
GPS	1.70	1.50	100	1.70	1.50
CIP	5.00	3.47	50	3.07	2.30
UHF RX	0.25	0.25	100	0.25	0.25
UHF TX	8.00	6.50	9.62	0.77	0.63
SBand TX	5.00	5.00	2.55	0.13	0.13
Battery Heater	4.64	4.64	1.00	0.05	0.05
Total				11.96	10.36
Power Gen				13.20	13.20
Margin				10.33%	27.39%

Note: CIP standby power consumption = 1.14 W. For CIP Avg power = $DutyCycle * PeakPower(or NominalPow)/100 + (1-DutyCylce/100) * Standby Power$.

When buck converter efficiency is taken to be around 95%, which is more realistic. Then power margin in case of peak power consumption rises to 31.06%, hence making sure no shortage of power happens during the mission.

Modes of Operation

The modes of operation have been divided into 4 modes based on battery's State Of Charge (SOC) and payload operation as shown below.

Table 5: Modes of Operation configuration

Subsystems	Emergency Modes		Normal Modes	
	Phoenix	Safe	Charging	Science
CDH, EPS, UHF RX	ON			
ADCS	OFF	Coarse Sun pointing	Fine sun pointing	Fine ref in RAM direction
CIP	OFF	Standby		ON
UHF TX	OFF	Beacon	As required	
SBand TX	Beacon	Beacon	As required	
Battery Heater	As required			

The CDH and EPS subsystems are always ON since they are the basic subsystems of the nanosatellite. The UHF is ON and by default configured in receive mode that allows the GS to make contact with the satellite. The Phoenix and Safe modes' purpose is to increase the SOC of the battery and hence together are called *emergency modes*. The Charging and Science modes of operation together are called *normal modes*. Following flow diagram is followed.

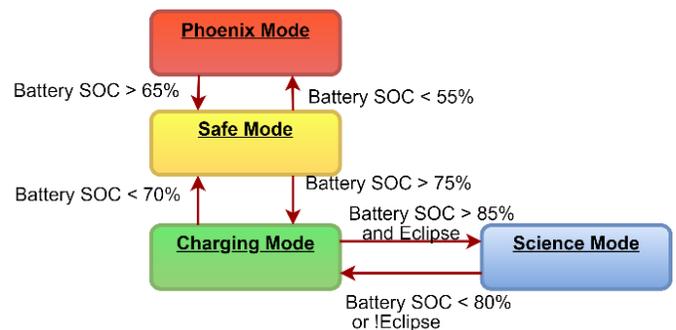


Figure 6 : Mode flow diagram

A day in Life Analysis

A day in life analysis simulates the operation of the satellite as per: Mode flow diagram. It gives the detail of battery Depth of Discharge (DOD) and details of power consumption by every subsystem.

The day of *June 12, 2020* was chosen for the analysis since the power generation was minimum in the orbits of the day. Figure 7 shows the battery's State of Charge (SOC) variation in the period on one day.

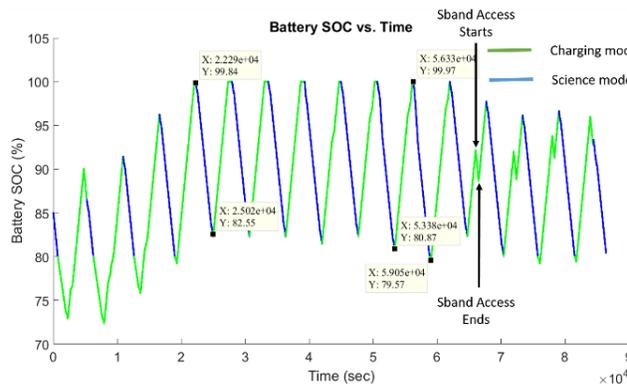


Figure 7: Battery State of Charge (SOC) vs. Time

The initial charge of the battery was taken as 85%. The battery comes back to 100% charge in 4 orbits.

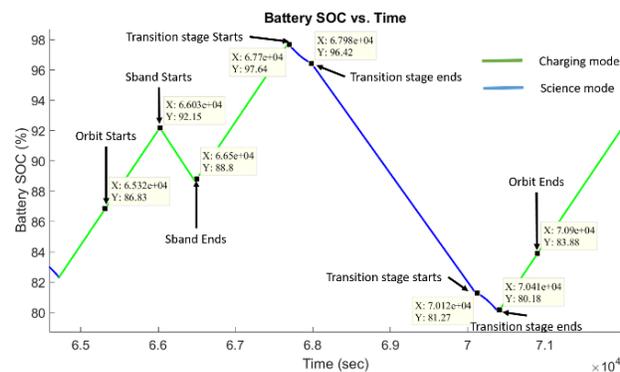


Figure 8: Orbit with SBand access

Shown in the Figure 8, during SBand access, which is access to LASP ground station, no power is generated and hence the battery's SOC decreases. The transition period of 5 minutes can be seen.

COMMAND AND DATA HANDLING (C&DH)

C&DH uses System On Module (SOM), which is provided by Emcraft and uses a System On Chip (SOC) provided by Microsemi. The SOC contains a microprocessor embedded in an FPGA. The off the shelf SOM is integrated with the rest of the nanosat by

a 'C&DH card'. The C&DH contains PC104 to interface with other subsystems.

The C&DH is responsible for collecting House Keeping data (HK data) from all subsystems and science data from the payload. It can configure subsystems and maintains a Real Time Counter (RTC) for time tagging the data. It is also capable of generating Pulse Width Modulation (PWM) signals, in parallel with other processes, in FPGA. The FPGA can implement more interfaces as per requirements, which are controlled by microcontroller via an Advanced High Performance Peripheral Bus (AHPB).

Electrical characteristics:

The following table gives electrical details of C&DH:

Table 6: Electrical characteristics of C&DH

Sr. no.	Parameter	Value
1.	Voltage	3.3 ± 0.3 V
2.	Peak Power	1.40 W
3.	Nominal Power	0.91 W
4.	Operating Temp	-40° C to 85° C

The CDH consumes 1.4 W when the processor is running at its full potential of 166 MHz and FPGA is more than 80% utilized. In practice, we will be using 10 MHz for the processor and FPGA will be less than 50% utilized.

System On Module (SOM)

SOM is an off the shelf module from Emcraft. It contains a 12 MHz quartz crystal and other clocks are derived from it by using PLLs present in SOM. It contains:

1. 32-Bit Arm Cortex-M3 processor.
2. 64KB embedded SRAM (eSRAM).
3. 512 KB embedded NVM (eNVM).

Interface Definitions

Table 7: Interfaces definitions

Subsystem	Interfaces
CIP	UART – RS422 (x1); CIP PPS – RS422 (x1)
ADCS	UART – RS422 (x1)
EPS	I ² C (x3); PWM (x3); Distribution control lines (x5); Deployment control lines (x3)
UHF Trans	UART (x1); GPIO lines (x6)
S-Band	I ² C (x1); SPI (x1); GPIO (x2)

C&DH card

The block diagram of the C&DH card is shown in Figure 9.

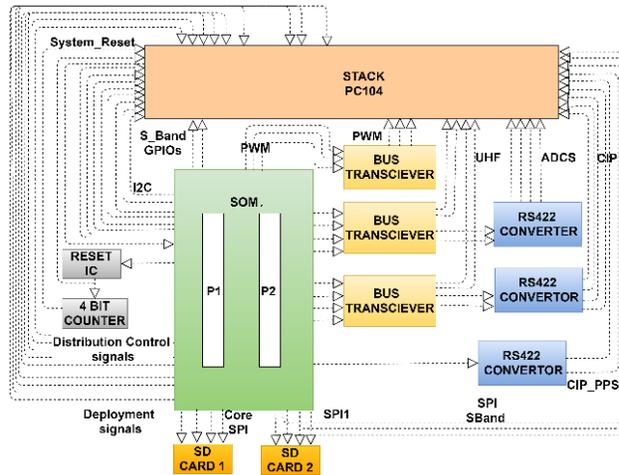


Figure 9: C&DH block diagram

1. The lines for RS422, PWMs and UHF GPIO lines pass through bus transceiver to protect the SOM from fluctuations in voltage and current. The bus transceiver also corrects the logic level to 3.3 V and 0 V for logic level 1 and 0 respectively.
2. Three RS422 Converter ICs (MAX3488) converts UART for CIP and ADCS, and GPIO line to RS422, which are required for the CIP.
3. The flight board contains 2, 32 GB SD Cards on two separate SPI bus. Using two provides redundancy if one of them fails.
4. A reset IC that contains a watchdog timer is connected to the SOM module, providing the first level of reset, also goes CLK of a 4-bit counter that counts the number of reset to form reset IC to C&DH. If counts go to 8 (b'1000) then it gives the signal for External System Reset to the EPS board. EPS cuts the power supply to all subsystems and turns the power supply ON back with a delay of 1 sec.

FLIGHT SOFTWARE

The flight software is responsible for collecting data and taking actions based on that data while storing relevant data on an SD-card. The flight software tasks, which are required to be done simultaneously, have been divided between microcontroller and FPGA. The task division is as follows:

FPGA

1. Generate PWM signal for Maximum Power Point Tracking (MPPT).

2. Polling UHF transmitter for received packets from Ground Station (GS).
3. Maintain Real Time Counter (RTC) for the satellite timing, with accuracy of 1ms.
4. Implement 2 UART, 1 I²C and 1 SPI core.

Microcontroller

1. Initializing various modules of the software
2. Collect and store data from various subsystems and act based on collected data.
3. Control UART, I²C, SPI, UHF Verilog code, PWM duty cycle generated by FPGA etc.

Sequence of Operation

The microcontroller controls the sequence of operations. Here, we present an *abstract* view of the sequence of operations:

1. Initialize GPIOs, bus transceivers, and SD-card. Initialize RTC to 0 and other variables of program.
2. Wait for prescribed amount of time given by the PSLV team.
3. Initialize sensors of EPS board by writing to their configuration registers.
4. Start MPPT with duty cycle of PWM = 1.
5. *Enter while loop.*
6. Give signal to external watchdog timer, if more than 1 s has been passed from last signal.
7. Take sensor data from EPS for MPPT and hence update duty cycle of PWM of Verilog core.
8. If 10 seconds has passed from last beacon, then transmit one beacon with most recent HK data on UHF frequency.
9. If deployment flag is 1 and 35 minutes have passed from last deployment and then try to deploy solar panel 1, 2 and UHF antenna in respectively for 1 min each else go to step 11.
10. Check UHF (Verilog implementation) for command from GS, if no command go back to step 6 else set flag 0 in Embedded Non-Volatile Memory (ENVM) as well as in running program, go to step 11.
11. Read all other sensors of EPS board. Decide one of the mode, normal (step 12) or safe (step 15) or phoenix mode (step 16).
12. *Normal mode:* Switch ON ADCS. Correct RTC using GPS time if required. Read sun sensors of ADCS to check for eclipse. If in eclipse go to Science mode (step 13) else Charging mode (step 14).
13. *Science mode:* Configure subsystem as per Table 5. Place ADCS in fine reference mode in RAM

- direction. Collect HK data from every subsystem. Get science data from CIP (payload) and store it. Go to step 17.
14. *Charging mode:* Do same as science mode except collecting science data from payload rather place it in standby mode (Table 5) and place ADCS in fine reference mode toward sun. Go to step 17.
 15. *Safe mode:* Configure subsystem as per Table 5. Place ADCS in coarse reference mode in sun direction. Collect HK data from every subsystem. Go to step 17.
 16. *Phoenix mode:* Configure subsystem as per Table 5. Increase the time interval of beacon from 10 seconds to 30 seconds. Go to step 17.
 17. Check command from GS and respond to it. Check SOC and sun sensor then determine mode for next sequence. Go to step 5.

ELECTRICAL POWER SUPPLY

The Electrical and Power System (EPS) of a nanosatellite is a very vital and critical subsystem that is expected to provide sufficient and regulated power for the operation of the entire spacecraft. The figure 10 shows the architecture of the power system:

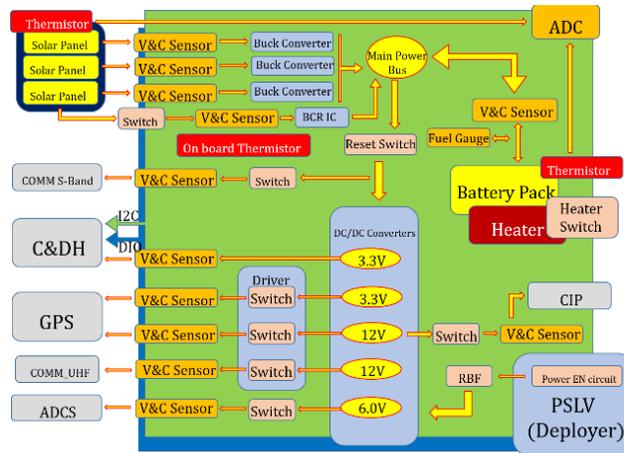


Figure 10: EPS architecture

1. The EPS is designed to accept power from 3 solar panels each with independent buck converters.
2. Mechanical relay is used as reset switch that on getting the signal from C&DH cuts off the battery from bus and then connects it back to the bus after a delay of approximately 1 second.
3. A Battery Charging Regulator (BCR) IC provides a redundant charging path when C&DH is not able to implement hill climbing algorithm of MPPT.
4. 3 DC-DC synchronous step down (buck) converters and 2 DC-DC synchronous step up

(boost) converters are provided in the design on load side to cater to voltage requirements of the loads.

5. The EPS features 2 critical I²C buses and a non-critical I²C bus on which the various VC (Voltage Current) sensors are placed and one Analog – Digital Converter (ADC) is placed to give temperature readings from thermistors.
6. VC sensors are placed to measure voltage across and current through the followings:
 - a. Solar panels and BCR IC.
 - b. Subsystems: CIP, CDH, ADCS, GPS (12 V and 3.3V), Comm (UHF and SBand)
 - c. Battery and battery heater.
7. Triple Modular Redundancy with Majority Voting Logic (MVL) is used for critical sensors i.e. the VC sensors for MPPT operation and fuel gauge.

Solar cells and Panels

AzurSpace 3G30C solar cells have been chosen for the mission because of their heritage on the MinXSS² mission. Their characteristics can be found in the following table:

Table 8: Solar cell characteristics

Sr. No.	Parameter	Value
1	Cell Volume	30.18 cm ³
2	Peak power voltage	2.411 V
3	Efficiency at 25°C	29.5%
4	Peak Power current	0.5044 A
5	Bypass diode	Yes

INSPIRESAT-1 has 3 panels for solar cells, one body mounted with 8 cells, and two deployable panels with 9 cells each.

Battery Pack

A 2S-3P configuration of Sparkfun Polymer Lithium-Ion Batteries are selected to meet the load requirements of the mission because of their heritage on the MinXSS mission. The battery characteristics are listed down in the table below:

Table 9: Battery Characteristics

Sr. No.	Parameter	Value
1	Nominal Voltage	3.7V
2	Nominal Capacity	2000 mAh/ 7.4 Whr
3	Dimension	60 x 54 x 5.8 mm
4	Charge cut-off voltage	4.2 V
5	Operation Temperature	-20°C to 60°C

EPS interfaces

The EPS has three I²C interfaces that are connected to the voltage current and temperature sensors on the board. The distribution of critical sensors has been done among the 3 I²C lines to have triple redundancy. The two components that have been identified as critical are Voltage and Current sensor (VC sensor) for solar panels and fuel gauge. Following are distribution of on the different I²C lines interfaces:

Table 10: I²C sensor distribution

Sr. No.	I ² C 0	I ² C 1	I ² C 2
1	VC sensor for solar panels	VC sensor for solar panels	VC sensor for solar panels
2	VC sensor for Battery, battery heater and BCR IC	Analog to Digital converter	VC sensor for GPS 12V
3	Fuel gauge	Fuel gauge	Fuel gauge
4	-	-	VC sensor for SBand, ADCS and CIP
5	-	-	VC sensor for C&DH, GPS 3.3V and UHF

In addition, GPIO lines from the CDH provide 3 PWMs for controlling the charging buck converters and control for distribution switches on the load side.

Table 11: GPIOs description

Sr. No.	Description	Number of GPIOs
1	PWMs	3
2	Power Distribution control signals	5
3	Deployment control signals	3
4	CONVEST (conversion start) ADC	1

COMMUNICATION

The communication sub-system receives and transmits data between the INSPIRESat-1 and ground. The spacecraft COMM and ground-station shall allow a data-rate of 193.5 MB/day during fast mode of CIP (payload), and 24.18 MB/day during normal mode.

SpaceQuest TRX-U transceiver

The layout and connector identification of TRX-U is indicated in the Figure 11. J2 is RF output connector, and the transmit power is 1 to 5 Watts. J1 contains all the interfaces to C&DH and power.

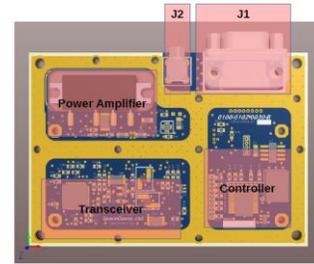


Figure 11: Layout and Connector Identification of TRX-U.

CPUT STX TRANSMITTER

CPUT STX is with a CubeSat Kit PC/104 form factor, and the modulation of it is QPSK. The data rate is up to 2 Mbps.

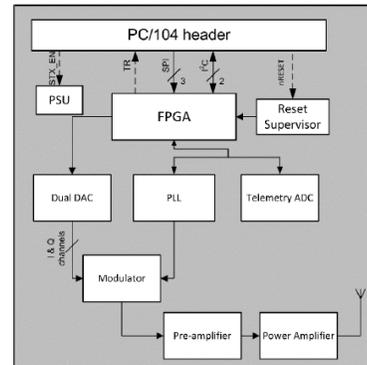


Figure 12: Block diagram of the CSK header connections. Broken lines indicate optional connections.

The only non-optional connection to the header (excluding power signals) I²C and SPI interface fits our Flight software FPGA well. All signal voltage levels are 3.0 V LVCMOS. A 50 Ω SMA connector will be used for transmitting RF.

Antenna for UHF and S-band

The UHF band uses the tape antenna and tests are being carried out at present.

The CPUT SANT S-band patch antenna has been selected to be used for high data rate communication with INSPIRESat-1. The antenna offers a default left hand circular polarization with a moderate gain of 8 dBi max. The frequency of operation is in the amateur band of the S-band frequency range (2.4 - 2.5 GHz). It is interfaced with the satellite through an SMA connector and weighs around 50gms. The dimensions of the antenna are 89 mm x 81.5 mm x 4.1 mm. The S11 10 dB bandwidth is around 90 MHz.

UHF Link Budget³

The basic parameters of our mission for calculating link budget are discussed in this section. Maximum and minimum are defined by different transmitting power. The orbital parameters in link budget follow the mission design. SpaceQuest TRX-U module is selected as our UHF transmitter. We are using 437 MHz. The elevation angle is 10° limited by the NCU ground station. Pass duration is about 7 minutes, and the data transfer per pass (full duplex) is 132 kB.

Table 12: Data parameters for calculation of UHF subsystem

Bit Error Rate / Probability of Bit Error	1E-5	[-]
Data Coding Scheme	GMSK/GFSK	
Required Bit Energy to Noise Ratio	9.6	dB
Data Rate	9600	bps (Hz)
Carrier to Noise Ratio Density	49.42	dB-Hz
Required Design Margin	3.00	dB
Minimum Pr/No	52.42	dB-Hz

Table 13: Parameters of the transmitters

Transmitter Parameters	Uplink		Downlink		Units
	MAX	MIN	MAX	MIN	
Transmit Antenna Gain	16.15	16.15	1.00	1.00	dBi
Transmit Antenna Beamwidth	30.0	28.0	120.0	120.0	deg
Transmit Antenna Pointing Accuracy	4.0	4.0	15.0	15.0	deg
Transmit Antenna Pointing Loss	-0.21	-0.24	0.00	0.00	dB
Transmitter System Losses	-6.4	-6.4	-0.3	-0.3	dB
DC Transmitter Power	380.88	24	8	6	W
Transmitter efficiency	0.197	0.197	0.25	0.25	
RF Transmit Power	74.995	4.726	2	1.5	W
RF Transmitter Power	18.75	6.74	3.01	1.76	dBW
EIRP	28.27	16.24	3.76	2.51	dBW

For the transmitter, Uplink represents our ground station and Downlink represents the UHF module on the satellite.

Table 14: Parameters of the receivers

Receiver Parameters	Uplink		Downlink		Units
	MAX	MIN	MAX	MIN	
Receive Antenna Area	0.020	0.020	3.800	3.800	m ²
Receive Antenna Efficiency	0.6	0.6	0.6	0.6	[-]
Receive Antenna Effective Area	0.012	0.012	2.28	2.28	m ²
Receive Antenna Gain	1.00	1.00	31.15	31.15	dBi
Receive Antenna Beamwidth	120.0	120.0	29.0	29.0	deg
Receive Antenna Pointing Accuracy	15.0	15.0	4.0	4.0	deg
Receive Antenna Pointing Loss	0.0	0.0	-0.23	-0.23	dB
Receiver Figure of Merit	-27.24	-27.24	1.64	1.64	dB/K
Receive Antenna Area	0.020	0.020	3.800	3.800	m ²
Receive Antenna Efficiency	0.6	0.6	0.6	0.6	[-]

As for receivers, Uplink is for the UHF module on the satellite and Downlink represents the ground station. Notice that there is an amplifier in the ground station (Downlink only), so we got more Receive Antenna Gain here.

Table 15: UHF subsystem link budget

Link Budget	Uplink		Downlink		Units
	MAX	MIN	MAX	MIN	
Propagation Losses	-152.9	-152.9	-152.93	-152.9	dB
Receive System Gain	1.00	1.00	30.92	30.9	dB
Received Power	-123.7	-135.7	-118.25	-119.5	dBW
Receiver Sensitivity	-141.0	-141.0	-152.00	-152.0	[-]
Power Margin	17.34	5.30	33.75	32.50	dBW
System Noise Power	-200.4	-200.4	-199.1	-199.1	dBW/Hz
Carrier to Noise Ratio Density	76.7	64.66	80.84	79.59	dB-Hz

Minimum Pr/No	52.42	52.42	52.42	52.42	dB-Hz
Link Margin	24.28	12.24	28.42	27.17	dB

The Table 15 shows us the quality of UHF communication in our mission. The estimating table shows us that we have positive link and power margin in the interval of maximum and minimum transmitting power, which means we will have a condition of communication that is good enough for the mission.

S-band Link Budget

The S-band transmitter is the Cape Peninsula University of Technology (CPUT) STX. The frequency is set as 2.402 GHz according to the capability of ground station at LASP in Boulder. The data rate is 2.0×10^6 bps (Hz), and the data transfer per pass (full duplex) is 27530 kB. Other system parameters are the same as in UHF calculations.

Table 16: Data parameters for calculation of S-band subsystem

Bit Error Rate / Probability of Bit Error	1E-5	[-]
Data Coding Scheme	QPSK	
Required Bit Energy to Noise Ratio	9.6	dB
Data Rate	2000000	bps (Hz)
Carrier to Noise Ratio Density	72.61	dB-Hz
Required Design Margin	3.00	dB
Minimum Pr/No	75.61	dB-Hz

Table 17: Parameters of S-band transmitter module (CPUT STX-01-00017)

Transmitter Parameters:	MAX	MIN	Units
Transmit Antenna Gain	7.00	7.00	dBi
Transmit Antenna Beamwidth	60.0	60.0	deg
Transmit Antenna Pointing Accuracy	15.0	15.0	deg
Transmit Antenna Pointing Loss	0.00	0.00	dB
Transmitter System Losses	-0.3	-0.3	dB
DC Transmitter Power	5	0.72	W
Transmitter efficiency	0.25	0.25	
RF Transmit Power	1.25	0.18	W
RF Transmitter Power	0.97	-7.45	dBW
EIRP	7.72	-0.70	dBW

We follow the specification of ISIS ground station. Receiver System Amplifier Gain is based on the datasheet of Transcom low noise amplifier.

Table 18: Parameters of S-band ground station (ISIS ground station specification)

Receiver Parameters:	MAX	MIN	Units
Dish Diameter	3	3	m
Receive Antenna Area	7.07	7.07	m ²
Receive Antenna Efficiency	0.6	0.6	[-]
Receive Antenna Effective Area	4.24	4.24	m ²
Receive Antenna Gain	31.35	31.35	dBi
Receive Antenna Beamwidth	5.1	5.1	deg
Receive Antenna Pointing Accuracy	0.1	0.1	deg
Receive Antenna Pointing Loss	0.00	0.00	dB
Receiver Figure of Merit	-0.38	-0.38	dB/K
Receiver System Amplifier Gain	38	38	dB

Table 19: S-band link budget

Link Budget	MAX	MIN	Units
Propagation Losses	-167.91	-167.73	dB
Receive System Gain	69.35	69.35	dB
Received Power	-90.84	-99.08	dBW
Receiver Sensitivity	-152.00	-152.00	
Power Margin	61.16	52.92	
System Noise Power	-196.87	-196.87	dBW/Hz
Carrier to Noise Ratio Density	106.03	97.79	dB-Hz
Minimum Pr/No	77.91	77.91	dB-Hz
Link Margin	28.12	19.88	dB

After applying amplifier, the link margin is *positive*.

ATTITUDE DETERMINATION AND CONTROL

The ADCS sub-system for the INSPIRESat-1 is being procured from BCT based out of Boulder, Colorado. The XACT is capable of 0.003° pointing accuracy in two axes and 0.007° in the third axis, which far exceeds the requirement of 5° in all three axes for the INSPIRESat-1 mission. The XACT has flight heritage on several nanosatellite missions including the successful MinXSS-1 mission developed at LASP at CU Boulder. The BCT XACT occupies 0.5U plus an additional 0.1U for the GPS receiver and has an approximate mass of 887g (excluding sun sensors and GPS). The XACT will communicate with C&DH over an RS-422. The XACT requires two 12V lines from

the EPS fed to the reaction wheels and to the XACT bus.



Figure 13: BCT XACT

The XACT has two modes of operation: Sun Point and Fine Reference Point. Sun point is the XACT safe mode that operates using a minimal sensor suite to point a desired spacecraft vector to the sun. Fine reference point uses the entire sensor suite available to the XACT (including GPS) to provide high precision pointing to any vector necessary. The XACT needs to be able to point the spacecraft -Z face to the sun during sun-lit portions of the orbit, point the +X face in the ram direction during eclipse, and maintain these orientations while experiencing disturbance torques. The XACT was delivered in April.

STRUCTURE

The Structure of INSPIRESat-1 is custom to the mission, with its design heavily driven by the need to use ISRO's IWL-150 Deployer. This Ring design means only one face of the spacecraft will be attached to the launch vehicle. This drove our design to have the ring side of the satellite be completely free of any other components. Furthermore, this side will be removable to allow the installation of the satellite's components. The fore-end ring will be attached to the bottom faceplate of the satellite via 6 M5x0.8 screws and remain with the nanosat post separation from the launch vehicle. The structure will be fabricated from aluminum 6061-T6. INSPIRESat-1 will use hinges and ADM developed and flown by MinXSS to attach and deploy the solar panels and UHF. Additionally, card rails will be used to hold the battery pack assembly in place. The main board stack comprised of EPS, CDH, XACT interface card, and the S-Band card, will be attached to two custom brackets that span the interior width of the nanosat. All other components will directly attach to the structure.

The structure will be composed of 4 pieces, 3 of them being unique (5 including the ring). These pieces are the Main Chassis, the Bottom Face-plate, and the board-stack End-Bracket. Below is the fully assembled CAD model and important views followed

by the results of the finite-element-analysis of stresses induced by launch.

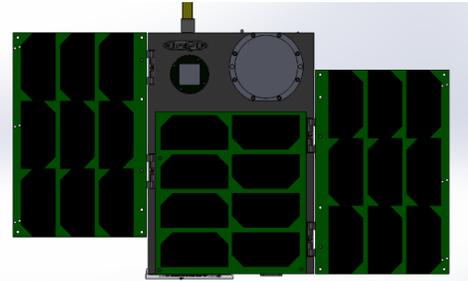


Figure 14: The solar panel side of INSPIRESat-1

The layout of INSPIRESat-1's internals is shown in this transparent bus view below. The battery pack is next to CIP just behind the pyramid sun sensor.

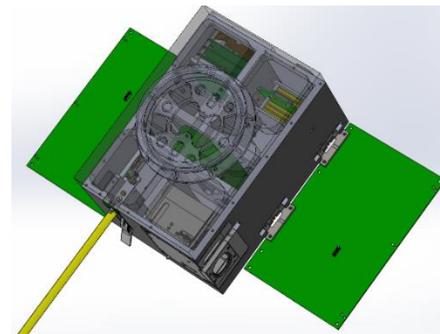


Figure 15: INSPIRESat-1 transparent view.

The shows the FEA of simulated launch loads. Testing all launch orientations possible, we found that when loaded through the width, the highest stresses occur. They fall well within the capabilities of the materials: Aluminum 6061.

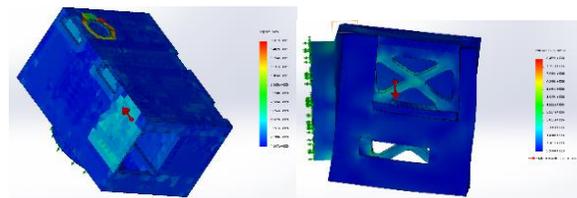


Figure 16: FEA mesh quality and worst case stress plot for 50g simulated launch acceleration.

Results show that the structure has survived an extreme case of loading comparable to almost 5 times that which it is expected to experience. In fact, the factor of safety throughout these scenarios remains above 30 suggesting the structure can be reiterated to cut mass. The total mass of INSPIRESat-1 is 8.6705 kg however with iteration this number will drop.

THERMAL

The thermal subsystem of the INSPIRESat-1 is responsible for maintaining the temperature of all of the components. The operating temperature range of CIP will drive the need for passive thermal control. To remain operational, CIP must remain between -10 and +50 °C. Additionally, the thermal subsystem must be able to cope with worst-case conditions. These being when the satellite is in eclipse (cold case) or in sunlit (hot case). To evaluate the worst-case hot case, a steady-state thermal analysis was performed using ANSYS software and a simplified geometry. The satellite was placed between the earth and the sun with its maximum area facing both. This produced the most incident heat flux from the sources named below. Several methods of heat transfer are in play and were accounted for and modeled properly in the analysis to ensure accuracy.

- Solar Radiation (Flux) Incident on the Nanosatellite = 1.412 kW/m² in early January to 1.321 kW/m² in early July
- Earth Albedo (Flux) Incident on the Nanosatellite = 0.4236 to 0.3963 kW/m²
- Earth IR Radiation = Nanosatellite and Earth's average temperature of 15°C radiation (Black body to Sat)
- Radiation to Space environment = -270.45 °C (2.7K)
- Internal Radiation = radiation between the internal surfaces of the nanosatellite
- Conduction = Heat's movement through the solid/contacting parts of the nanosatellite
- Internal Heat Generation = Heat generated by the electrical components of the nanosatellite

These loads were applied accordingly and the different materials of the model specified. This includes thermal conductivity, absorptivity, and emissivity. The emissivity of materials can be changed with coatings such that it can be used as a tuning knob for the thermal design. Additional copper thermal straps can be used to alleviate areas requiring higher thermal rejection. As we get information that is more definitive on the launch and the orbit INSPIRESat-1 will be placed in, we can adjust the design wherever needed. Results, shown in figure 17 and 18, show that the antenna experiences the maximum and minimum temperature. The solar panels are unsurprisingly hot as well as the regions around the electronics during the hot case.

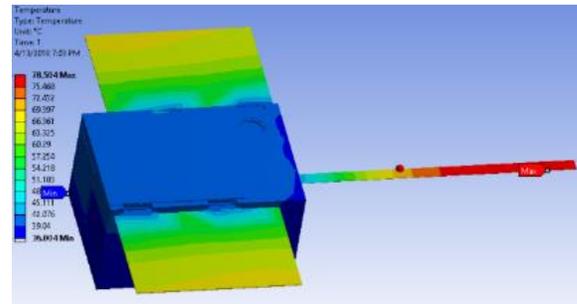


Figure 17: Thermal analysis of hot case of INSPIRESat-1.

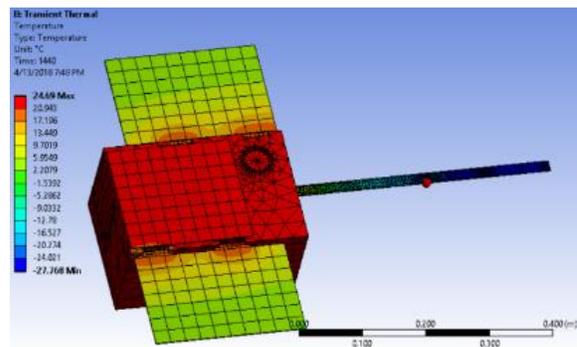


Figure 18: Thermal analysis of 24-minute ECI case of INSPIRESat-1.

CIP experiences temperatures between 22 and 40 °C, well within its operational temperature. The average temperature of the bus at the end of a 24-minute eclipse was found to be ~24 °C.

CONCLUSION

The INSPIRESat-1 is being developed via an international collaboration not usually seen on this type of mission. The mission will measure properties of the Earth's ionosphere to better understand irregularities like plasma bubbles and the midnight temperature maximum. The INSPIRESat-1 will go through CDR this July and will experience a surge in development as students from each institution join together for the summer in Boulder, Colorado to continue work. The next few key steps include printing and validating the program developed boards, as well as standard engineering tests like thermal vac and vibration tests.

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