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SYSTEM ENGINEERING AND INTEGRATION OF PRATHAM, INDIAN INSTITUTE OF TECHNOLOGY BOMBAY'S FIRST STUDENT SATELLITE

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ABSTRACT

Students from the Indian Institute of Technology Bombay (IITB) are currently in the process of building a fully functional microsatellite named 'Pratham', which is slated for launch by Indian Space Research Organization (ISRO) in the first quarter of 2010. This paper discusses the various aspects of System Engineering and Integration involved in the making of Pratham. The System Requirements from the Mission Statement and environment are broken down into Sub-System Requirements. After capturing inter Sub-System requirements, the target parameters for each of the Sub-Systems are created. These target parameters are tested at Sub-System level using Level 1 Test. Two to three Sub-Systems come together to perform Level 2 Test, like Hardware In Loop Simulation (HILS), Communication and Ground Station check, etc. Finally Level 3 test like Vibration, Thermovac, etc. are performed for the whole satellite. While integrating the satellite, the use of Integration Sequence and strategies for wire touring are explained.

Keywords: System Engineering, Integration Sequence, Wire Routing

I. INTRODUCTION

The IIT Bombay Student Satellite Project is a landmark project taken up by the students of the institute. The plan is to build and launch atleast 5 satellites into orbit within the next few years and make IIT Bombay a respected center for advancement in Satellite and Space Technology, in the world. These Satellites will also serve as test-beds for new technology that is being developed within the institute and needs space qualification. '*Pratham*', which means first in Sanskrit, is the first satellite under this project. Work on Pratham started in August 2007 when the idea of a student satellite was conceived by the students and its feasibility was proved to the institute's faculty. Subsequently, the Indian Space Research Organization (ISRO) has supported the project through technical guidance, reviews and equipments. Over the years, the project has undergone a number of successful design reviews and is going to be launched in the 1st quarter of 2011 onboard ISRO's PSLV rocket. A group of 30 students, across all departments, work on the Project at IIT Bombay. They are supported by a team of faculty mentors at IIT Bombay and a group of scientists from ISRO.

In this paper we shall discuss the various aspects of Systems Engineering and Integration involved in the making of Pratham. Using a 'V-model', the System Requirements and Sub-System Requirements are captured, which they have to meet by the individual Sub-Systems at the end of the design cycle. The Operational Sequence of the Satellite is explained. The Level 1, Level 2 and Level 3 testing stages are discussed. Integration of a student satellite can be troublesome if not planned and executed thoroughly. Hence the approach applied towards Pratham's integration is elaborated, followed by the Integration Sequence and strategies for routing of wires. Overall, it is envisaged that this paper will give an insight into efficient Systems Engineering and Integration of a student satellite.

II. SYSTEMS ENGINEERING

For any large project, the inter-disciplinary field of Systems Engineering is a must. Systems Engineering captures how each of the Sub-Systems that form the System interact with each other and how the System interacts with the environment when it is performing it mission. Hence, the first step will be defining the mission and success criteria for the Pratham Satellite.

A. Mission Statement

The Mission for Pratham, IIT Bombay's First Student Satellite is

1. Acquiring knowledge in the field of Satellite and Space Technology.
2. Have the Satellite entirely designed by the student body of IIT Bombay.

3. Have the satellite launched, Measure Total Electron Count of the Ionosphere above IITB.
4. Involve students from other universities in the Satellite project.

Since IIT Bombay is a technological institute and this is the first time a project of this kin is being taken up, a lot of importance is given to learning. Moreover, it is felt that following the popular concept of CDIO (Conceive, Design, Integrate and Operate) while working on this project will be an invaluable experience for the students and the institute. The Payload of the Satellite is measurement of Total Electron Count (TEC) of the Ionosphere. Finally, the Pratham team believes in saring all the knowledge that they have been fortunate to learn through this project. Hence they have encouraged students from other universities to build their own satellites or build ground stations for Pratham at their universities to measure TEC. Three National Ground Station Workshops have been held and around 11 universities in India and 2 in France are collaborating with the Pratham project. Some of the simulations developed for Pratham have been web-enabled to make a Virtual Laboratory.

When all the mission statements are fully satisfied, the satellite will be fully successful. But each of these statements need not have equal importance, hence the success criteria of the Pratham project is:

Table 1: Success Criteria of Pratham

Description	Mission Success
Flight Model ready	85%
Beacon Signal received	90%
TEC measurements at IITB	95%
Satellite functional for 4 months	100%

A lot of importance is attached to finishing the Flight Model, since that will mean that all the learning that has gone into making of the satellite is a success. Subsequently when the satellite is launched and we receive Beacon and TEC data, further success is given to the mission. Finally, it is felt that if the satellite works for 4 months in space, it will be enough to justify the effort that has gone into building it. Some of the important parameters of the Pratham Satellite are:

- Weight: ~10 kgs
- Size (excluding monopoles): 260mm cube
- Payload: Measuring TEC
- Planned Orbit: 10:30 polar sun-synchronous, 817km altitude
- Downlink at 2 frequencies (145.980MHz and 437.455MHz), Uplink used as kill switch
- Three axis stabilized
- 4 months mission life
- Launch Vehicle Interface to be provided by ISRO

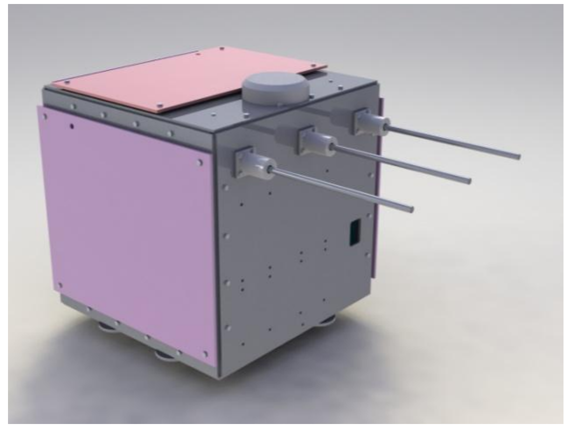

Figure 1: Rendered View of Pratham Satellite

The Satellite is a 26 cm cube, and it has six sides. The names of the sides are as follows:

- **Nadir Side:** This is the bottom plane of the satellite. The Launch Vehicle Interface (LVI) is attached to the lower surface of this side. It houses the battery box.
- **Zenith Side:** This is the top plane of the satellite. It is opposite the Nadir Side. It houses the GPS and its antenna, the central Sunsensor board and a magnetoruer.
- **Sun Side:** Since the satellite will be in a Polar Sun-synchronous orbit, this side will always face the sun. It houses the Power circuit and a magnetorquer.
- **Antisun Side:** This side never faces the sun. It is opposite the Sun Side. It houses the 3 monopole antennae, the transmitter circuit for the telemetry and the beacon.
- **Leading Side:** The normal to this side, pointing away from the centre of the satellite, points along the direction of the velocity vector of the satellite in orbit. It houses the On Board Computer circuit and a magnetorquer.
- **Lagging Side:** The normal to this side, pointing away from the center of the satellite, points opposite to the direction of the velocity vector of the satellite in orbit. It is opposite to the Leading Side. It houses the Magnetometer and the Uplink circuit.

B. Introduction to Sub-Systems

The entire work on Pratham is done by 9 Sub-Systems. A brief introduction of all the subsystems is presented below.

1. Payload Subsystem

The goal of the Payload Subsystem is to measure the Total Electron Count (TEC) of ionosphere with 0.1 TEC units accuracy and then create a TEC map of the country. The TEC data could be used for Ionospheric Tomography if the ground stations are on the same longitude.

A linearly polarized radio wave passing through an ionized medium with a magnetic field in the direction of propagation undergoes a rotation in the plane of polarization. This effect is called Faraday rotation. Onboard the Satellite, two parallel monopoles transmit linearly polarized waves at two different frequencies (145.98 MHz and 437.455 MHz). The planes of polarization of the signals from the satellite, which have passed through the ionosphere, can be measured by crossed yagi antennae at the ground station. Measuring the difference between the planes of polarization for the two frequencies removes the need for measuring the attitude of the satellite precisely. The goal of measuring TEC up to 0.1 TECU accuracy places severe constraints on the parallelism of the monopoles, the polarization purity of the monopoles and the least count of the detector at the ground station.

2. Communication and Ground Station Subsystem

The primary goal of the Communication and Ground Station subsystem is to establish a communication link between the Pratham satellite and the ground station at IIT Bombay and measure the plane of polarization of the signals. Onboard the satellite, there are 3 pre-deployed monopole antennas, 2 of which are used for transmitting linearly polarized signals with a polarization purity of greater than 99.9% (30dB). The monopoles are mounted away from the Nadir Side to obtain the desired radiation pattern. There is a low bit rate Beacon at 145.980 MHz frequency transmitting throughout the world in OOK modulation. There is also a high bit rate (1.2kbps) 437.455 MHz circuit for downlink of data only above India and France.

The frequency allocation process necessitated the need for ground station to be able to switch-off the transmitter of the satellite as per International Amature Radio Union (IARU) regulations. Hench an uplink circuit has been added as a kill switch for the satellite in case the satellite starts transmitting at a non-allocated frequency band.

At the ground station at IIT Bombay, 4 crossed yagi antennae are mounted on a rotor to track the satellite and receive data and measure the plane of polarization of the two signals from the satellite. The ground station at IIT Bombay is setup at the terrace of the main building of Department of Aerospace Engineering.

3. Attitude Determination and Control Subsystem

The goal of the Attitude Determination and Control subsystem is to stabilize the satellite after it is jettisoned from the launch vehicle during launch. It has to then maintain 3 axis attitude stabilization of the satellite. Onboard the satellite, there are 6 sun-sensors (on all sides), 1 magnetometer and 1 GPS for attitude and position sensing. There are 3 magnetorquers mounted along 3 different axes for attitude control. There is also a sun-sensor board where all the analog wires from the sun-sensors converge, and the digital information issent to the On Board Computer.

4. On Board Computer Subsystem

The On Board Computer subsystem comprises of one circuit board which interfaces with all sensors, actuators, Power circuit and the Communication circuits. It is the mind of the satellite, which controls every action onboard the satellite.

5. Power Subsystem

The power system comprises of one circuit board which controls the power to be delivered to every component onboard the satellite. For power generation, there are solar panels on 4 sides of the satellite and a battery top store the power.

6. Structures Subsystem

The aim of the Structures subsystem is to validate the Satellite will be able to withstand the loads during launch. All the components should be safe and working after the launch. The Satellite structure should also be able to withstand the thermal loads arising in the orbit.

7. Thermals Subsystem

The Thermals subsystem aims to maintain a cycle of temperature within the satellite within the narrow range (0 to 40^0C) which lies around the normal terrestrial temperatures, minimize spatial gradients of temperature, dissipate excess heat generated by components and maintain sensitive components within their specified functional ranges of temperature. The thermals subsystem essentially uses passive methods to maintain temperatures in the required ranges and dissipate localized heat generated by circuits.

8. Quality Subsystem

The Quality subsystem is responsible for maintaining the quality standards within the Satellite project. A goal has been set to keep the probability of failure during the mission life of Pratham to less than 2%. Apportioned QA for each of the Electrical Sub-Systems is given in the table. Mechanical QA is difficult to handle since it is always assumed to be ~1, i.e. there is no scope for any failure. Hence there should be large safety factors in the designs. A clean room of 100000 class has been built for the fabrication and storage of the satellite and its components.

Table 2: Apportioned Electrical Reliability

Subsystem	Reliability
Communication	0.9980
Power	0.9950
Controls	0.9990
On Board Computer	0.9950
Thermal	0.9995
Structure and Mechanisms	1.0000
Integration	0.9990

9. Integration Subsystem

The Integration subsystem has the job of bringing all the subsystems together to make a complete system. Their tasks are dealt in detail in the next section.

III. SYSTEM AND SUB-SYSTEM REQUIREMENTS

The V-model is a graphical representation of the systems development lifecycle. It summarizes the main steps to be taken from the initial conceptual design of the system to the final validation of the system.

The Mission Statement and the Environment (space, launch vehicle, etc.) give rise to System Requirements. These System Requirements are handed down to the individual Subsystems. The Subsystems also interact with each other to give Subsystem Requirements. Finally from all these requirements come the Critical Parameters which the individual Sub-Systems have to design and satisfy.

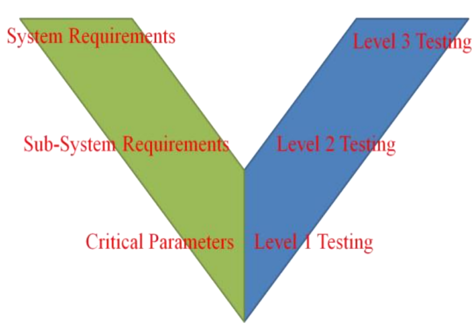

Figure 2: V Model for Pratham Project

Similarly, the critical parameters are tested by the Subsystems in Level 1 testing. 2-3 Subsystems get together and do Level 2 testing where the interaction between these Subsystems is checked. The final integrated Satellite level testing is done in Level 3 testing like vibration testing, thermovac, etc. On-board computer In-Loop Simulation (OILS), is a setup for simulating the on-board computer with inputs similar to those that it may experience in the satellite. It will help identify bugs and shortcomings of the hardware and software of the On-Board Computer.

A. System Requirements on the Sub-Systems

The System Requirements on the individual Sub-Systems from the Mission Statement and the Environment are as follows:

Requirements on the Payload Sub-System

- Payload Sub-System shall measure the Total Electron Count (TEC) of Ionosphere above IIT Bombay with 0.1 TEC units accuracy.

Requirements on the Communication and Ground Station Sub-System

- Communication Sub-System shall transmit with the 1st monopole (Beacon) all over the world at a certain duty cycle (25%).
- They shall transmit data from the Satellite over India, using the 2nd monopole to the ground station at 1.2 kbps.
- They shall setup a ground station at IIT Bombay.
- They shall design low-cost (less than $ 500) ground stations for other universities.

Requirements on the Attitude Determination and Controls Sub-System

- Attitude Determination and Controls Sub-System shall measure the attitude to 5^0 degrees accuracy along all axes.
- They shall measure the instantaneous position of the Satellite in orbit to 1 kilometers accuracy.

Requirements on the On Board Computer Sub-System

- On Board Computer Sub-System shall carry out pre-launch checks of the Satellite before launch.
- They shall store the Health Monitoring Data onboard the Satellite when in orbit, as per the Data Budget.

Requirements on the Power Sub-System from the System

- Power Sub-Systems shall recharge the batteries before launch using external charger.
- They shall detect the deployment of the Satellite into orbit using the SNAP switch.

- They shall harness the solar power falling on the Satellite and store it in batteries.

Requirements on the Structures Sub-System

- Structures Sub-System shall make the Satellite frame such that it can withstand the launch loads.
- They shall make the Satellite frame such that it can withstand atleast 4 months of thermal loading cycles.

Requirements on the Integration Sub-System

- The Integration Team shall provide the Access Port and the Battery Charger Port for the pre-flight checks and charging the batteries.

Requirements on the Quality Sub-System

- Quality Team shall make sure that the Satellite is made as per the Quality standards deemed necessary by ISRO for the success of the project.
- They shall lay down rules, handling procedures, test procedures, etc. to meet the Quality standards and do the reliability analysis of the Satellite.
- They shall setup the 1lakh class Clean Room in IIT Bombay for Pratham.

B. Requirements on one Sub-System from another Sub-System

Requirements from Payload Sub-System to Communication and Ground Station Sub-System

- Communication Sub-System shall maintain the polarization purity of both the monopoles better than 30 dB, i.e. an axial ratio of 1000:1.
- They shall maintain an accuracy of 0.3dB in signal strength ratio measurement at the ground station.
- They shall detect the difference is the polarization angle between the two signals at the ground station with an accuracy of 1 degrees.

Requirements from Communication and Ground Station Sub-System to Power Sub-System

- Power Sub-System must supply the 1st monopole (Beacon) with 1.5W when it is switched on.
- Power Sub-System must supply the 2nd monopole with 4W when it is switched on.
- Due to the operational sequence, the average power needed by both the monopoles over one day is 0.58W.

Requirements from Communication and Ground Station Sub-System to Attitude Determination and Controls Sub-System

- Attitude Determination and Controls Sub-System shall maintain the Satellite at 0^0 pitch and 0^0 roll along the orbit reference frame, with a maximum error of ±10 deg in both these axes.

Requirements from Attitude Determination and Controls Sub-System to On Board Computer Sub-System

- OBC Sub-System shall execute the Control Law as per the operational sequence.
- They shall interface with the Magnetometer, GPS and 6 Sun-Sensors.
- They shall drive the 3 magnetorquers using PWM.

Requirements from Attitude Determination and Controls Sub-System to Integration Sub-System

- Integration Team shall make the principal axis of the Satellite coincide with the geometric axis.
- They shall make the Satellite meet the conditions for Static stability.
- They shall place the 3 magnetorquers on 3 sides along the 3 body axis, namely the zenith, the leading velocity and the sun-side.
- They shall place the GPS on zenith and expose the antenna to space.
- They shall place the magnetometer at the position with least magnetic disturbances.
- They shall place the 6 Sun-Sensors on the 6 sides with unobstructed field of view.

Requirements from Communication and Ground Station Sub-System to On Board Computer Sub-System

- OBC Sub-System shall send packets of data at 1.2kbps with AX25 communication protocol when Satellite is in mode 3, as per operational sequence.

Requirements from On Board Computer Sub-System to Power Sub-System

- Power Sub-System shall supply continuous power of 1W to the OBC Sub-System.
- OBC Sub-System shall update Power Sub-System every two second, with the list of components that should be on and the rest are to be switched off.
- Power Sub-System shall send HM data of its sensors when the OBC polls for data.

Requirements from Power Sub-System to On Board Computer Sub-System

- Power Sub-System shall give a hard interrupt of highest priority if the power drops below a certain threshold. Then OBC shall get ready to be shut down within the next 2 seconds.
- Power Sub-System shall inform OBC Sub-System if some component ‘misbehaves’ and had

to be shutdown. The decision to shut it down shall be taken locally at Power Sub-System.

- The Power Sub-System shall attempt to revive the 'misbehaving' component by restarting it.

Requirements from Power Sub-System to Integration Sub-System

- Integration Team shall place solar panels on the 4 sides, namely sun-side, zenith, velocity-leading side and velocity-lagging side.
- Integration Team shall make sure that shadows due to other deployed parts shall not fall on the solar panels.

Requirements from Payload Sub-System to Attitude Determination and Controls Sub-System

- Attitude Determination and Controls Sub-System shall maintain the Satellite at 0^0 yaw along the orbit reference frame, with a maximum error of ±10 deg in this axes.

Requirements from Power Sub-System to Attitude Determination and Controls Sub-System

- During Mode 2, Attitude Determination and Controls Sub-System shall try to achieve an attitude such that maximum solar irradiation falls on the solar panels.

Requirements from Power Sub-System to Thermals Sub-System

- Thermals Sub-System shall protect the solar panels from heating above 70^0C.
- They shall maintain the temperature range of the battery within 0^0 to 30^0C.
- They shall remove the excessive heat from Power Circuits, since the temperature range of the components (industrial grade) is -40^0 to +85^0 C.

Requirements from Communication and Ground Station Sub-System to Thermals Sub-System

- Thermals Sub-System shall protect the monopoles from heating above 100^0C.
- They shall remove the excessive heat from the 2 Monopole circuits, since the temperature range of the components (industrial grade) is -40^0 to +85^0 C.

Requirements from On Board Computer Sub-System to Thermals Sub-System

- They shall remove the excessive heat from OBC Circuits, since the temperature range of the components (industrial grade) is -40^0 to +85^0 C.

Requirements from Thermals Sub-System to Power Sub-System

- Power Sub-System shall supply power to the Battery Heater Circuit. (values TBD)

Requirements from Integration Sub-System to Power Sub-System, Attitude Determination and Control Sub-System, Communication and Ground Station Sub-System and On Board Computer Sub-System

- The final circuit board should have a natural frequency above 120Hz.
- The size of the circuit board should be such that it can be mounted on the circuit harness.

Requirements from Quality Sub-System to Power Sub-System, Attitude Determination and Control Sub-System, Communication and Ground Station Sub-System and On Board Computer Sub-System

- Extensive testing before launch to prevent Infant Mortality.
- Satellite is designed for a life of 4 months; hence probability of failure should be below 2%.
- Soldering and Circuit Design guidelines given by ISRO, will be followed

IV. OPERATIONAL SEQUENCE

The Satellite passes through various stages of operation (modes). The different modes of operation of the Satellite are listed below and the flowchart describes the transfer from one mode to another.

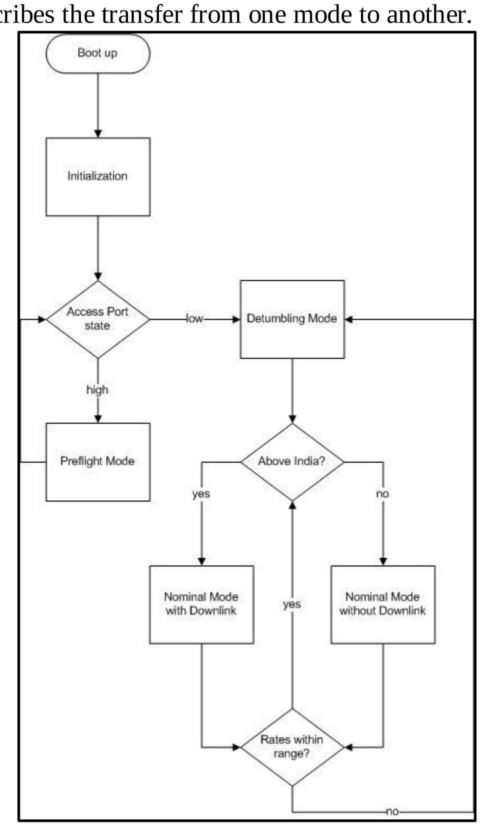

Figure 3: Flowchart for the Modes of Operation

Mode -1: Pre-flight checks

- Satellite shall be inside the Clean Room at the launch site.
- The access ports shall be used to check the Satellite's health.
- The batteries shall be charged to full capacity.
- The Satellite is ready for launch and mounted on the Launch Vehicle.
- Before launch, the RBF pin shall be removed from Power circuit.
- This mode starts about 6 days before launch. (T – 6 days)
- In the event of a delay, the batteries shall be recharged after 30 days on the launch vehicle.

Mode 0: Liftoff

- Satellite shall be inside the Launch Vehicle. This mode starts with liftoff and ends within 17-22 minutes after launch (T 0).
- All Sub-Systems shall be switched off.
- The Satellite shall be deployed into orbit by the Launch Vehicle, using the Launch Vehicle Interface.
- The SNAP circuit (Deployment Switch) shall detect the Satellite is deployed.

Mode 1: Detumbling

- The SNAP circuit shall switch on the Power circuit.
- The Power circuit shall switch on the other components in the following order.
  - OBC circuit
  - Beacon circuit
  - All control sensors and magnetorquer
  - Monopole 2
- All processors, memory units, sensors and actuators shall be initialized by the OBC.
- Health Monitoring checks shall be done for all the components by the OBC.
- The 2 Monopoles shall be deployed, before detumbling begins.
- When Satellite is deployed it has rotational rate about 5deg/sec on all 3 axis, this shall have to be reduced to 0.1deg/sec for nominal mode operation. This process is called Detumbling. It takes about 2-6 orbits, or a maximum of 9 hours to detumble completely.

Mode 2: Nominal operation without Downlink

- This shall be the normal mode of operation of the Satellite in orbit but when not over India.
- Beacon shall be switched on. It will on a 25% duty cycle.
- The Monopole 2 shall be switched off.
- The Satellite attitude shall be oriented such that maximum power will be received by the Solar Panels.
- Health Monitoring data as per the Data Budget, shall be stored by the OBC.

Mode 3: Nominal operation with Downlink

- This shall be the normal mode of operation of the Satellite in orbit when it is over India.
- Beacon shall be switched on at 100% duty cycle.
- The Monopole 2 shall be switched on such that:
  - When Satellite will be over India but not over IITB, Mon2 will transmit the instantaneous position and attitude data.
  - When Satellite will be over IITB, Mon2 will transmit the 64kB of stored data in memory; corresponding to the HM for the previous 24 hrs.

Mode 4: Emergency Mode

- This mode shall be entered when some over-current error is encountered in any component on the Power board. The Power board switches off the component's power supply immediately and tries to revive after it every 50 seconds.

Mode 5: Safe Mode

- This mode shall be entered when the power drops below a threshold.
- The components will be switched off in the following manner, by the Power circuit:
  - monopole 2
  - All control sensors and magnetorquer
  - OBC circuit
  - Beacon
  - Power circuit

V. INTERNAL ELECTRICAL ROUTING

Pratham has an arrangement of electrical circuits in a surface mounted manner, where each circuit boards rests on its designated mount against the structural panels. The advantages yielded by this configuration are reliable electrical grounding of all circuits and efficient thermal control using purely passive methods. However, such an interior arrangement gives rise to complexity in the routing of electrical connections between different circuits, necessitating detailed study and design of a suitable scheme for making the connections.

A. Requirements on electrical routing

- The wires used for electrical routing should be of appropriate current rating to withstand maximum possible currents expected, with a factor of safety.
- The insulation used for the wires must not undergo outgassing in space environments.
- The slack length of wires must be within 5mm to prevent harmonics being set up within the slack

portions, hence wire lengths for each connection must be known to this accuracy.

- Wires carrying high power must be separated from wires carrying analog or digital data, to avoid corruption of the signals by noise.
- Wires have to be clamped periodically to the structure and the clamping positions are required to be determined.
- The wires have to be routed parallel or perpendicular to the axes of the satellite as far as possible, to provide clarity and aid in integration of the satellite.
- There must be minimum bend radius of 6 times the diameter when changing direction of a wire bundle, as given by ISRO guidelines.

B. Selection of wires

- The peak current carried between any 2 points onboard the satellite is limited to a value of 0.9A by current limiters. Hence, wires with a minimum current rating of 1A were considered, that is, AWG26 and higher. To provide a factor of safety, AWG24 wire with higher current rating was selected for Pratham.
- To avoid breakage of electrical connections by snapping of a single wire, multistrand wires were selected for higher reliability.
- Equivalent commercial grade wires were selected in place of space grade wires, with care being taken to select correct temperature range of operation and Kapton insulation which does not outgas.
- In case of analog data carried from the sunsensors to the analog-to-digital converter circuit, the wires are partially routed in the same bundle as the wires carrying power from the solar panels to the batteries, as the sunsensors are pasted on the solar panels. To avoid corruption of analog data by noise, twisted pair shielded instrumentation cables were selected.
- Coaxial cables were chosen for communication wires as the ground mesh surrounding the signal wire prevents corruption of the signal by noise.

C. Algorithm for optimal routing

A systematic procedure for determining the routing of wires onboard Pratham was followed, instead of a method involving only intuition, to achieve optimum routing in fewer steps.

The details of starting and ending connectors on each circuit, the number of wires going from one connector to its counterpart and the type of wire (power , data or analog) were tabulated, to help in enumerating the connections and maintaining records.

The next step towards arriving at a wire routing schematic was to make a 3-Dimensional transparent model of the satellite to help in visualizing all possible paths along the satellite interior. All possible paths were listed down for each connection. Each path was then evaluated using the requirements on wire routing and unsuitable paths eliminated.

For the N connections $\{C_1, C_2, \ldots C_n\}$ onboard, each i^{th} connection having m paths $\{C_{i1}, C_{i2}, \ldots C_{im}\}$, a set of N paths $\{C_{1i}, C_{2j}, \ldots C_{nk}\}$ was selected. Each such set was evaluated and sets conforming to all requirements were chosen. The simplest such set was represented in 3D on a model for easy visualization to determine rough wire lengths, bending radii and clamp positions. It is proposed to write a code using this method thus automating the process of wire routing for a satellite.

The interior of the satellite was modeled using sheet metal forming with electrical circuit replicas attached. Routing was performed with the actual wires used onboard to check the physical correctness of the wire routing scheme. This model helps to get better approximations for the lengths of each connection allowing for the wire thickness and flexibility. It brings forth the practical problems in manual routing as well as in integration sequence.

D. Implementation of electrical connections

Clamps to hold the wires in place are pasted onto the panels at predetermined locations using specified epoxy adhesives. Cable channels are also pasted on the panels following the paths where wire bundles will be run on that panel. As each panel on the satellite is fitted, the appropriate electrical connections leading from that panel to already integrated panels are made.

Each pair of communicating connectors has a bundle with the appropriate number of wires running between them. The correct lengths of wire are measured out for each connection and cut with a margin of 5mm on either side, to allow for the thickness of the cut. Multiple pieces of heat shrinkable tubing are cut, each of 5mm length, and strung on the wire bundle. The contacts at either connector are crimped and fitted with heat shrunk tubes. At every 50mm interval, the intervening pieces of heat shrinkable tube are tightened to act as lacings for the wire bundle.

The wire bundle is attached to the clamps and securely fastened using cable ties. After each bundle of wires is routed, electrical connectivity is immediately tested to ensure proper connection and facilitation detection of faults in routing.

VI. INTEGRATION SEQUENCE

The Integration Sequence is the step-by-step ordering of operations performed to assemble the satellite giving details of the procedure, parts involved, location on the satellite, clamping of the satellite, orientation of the satellite, tools required, forces and torques to be applied, guidelines to be followed and checklist of preceding tasks to be completed.

A. Need for Integration Sequence

In the process of integration often a problem of accessibility is faced due to space crunch and overlapping parts if the integration has been carried out in a haphazard fashion. Sometimes integration of component is postponed till the last stage and then the component turns out to be inaccessible.

Sensitive components might be unnecessarily integrated at an earlier stage and then might get damaged in further steps.

Another major problem faced during the integration is closing the cube of the satellite. If this is done in a haphazard fashion, the wiring of the components might become a major problem. Thus deciding the order in which the cube is closed is an important function of the integration sequence.

Having a predefined integration sequence will help the integrating personnel in having a clear idea of the procedure that will be followed in the integration of the satellite. This avoids the problems enlisted above.

B. Basic principles followed in integration

1. The sequence has been decided in such a manner that the person performing the integration has adequate space for comfortably handling the tools.
2. Fixtures have been designed keeping in mind the integration sequence such that the person performing the integration needs to support minimal number of components giving him better freedom in handling the tools.
3. Integration of sensitive components like the sunsensor and the solar panels is delayed as far as possible as they are very susceptible to handling damage arising from tools hitting their surfaces.
4. Each integration step involving screws has a predefined fastening sequence of the screws to minimise warping of the plate as even the slightest warp might affect the hole alignment in the assembly.
5. Each screw must be tightened to a predefined torque value to avoid any imbalance in torques resulting in warping of plates.

The Integration Sequence of Pratham has been divided into 5 levels based on clamping requirements, sensitivity of parts being assembled and overlapping of parts on the structure.

1. Level 1

This level deals with the integration of the components onto the individual panels and is to be undertaken first. All the Circuit Boards and the GPS and the magnetometer modules are included in this level. Fixing of clamps and cable channels for routing on each panel is also done.

2. Level 2

Level 2 deals with integrating the 5 sided incomplete cubic structure on which the external components can be mounted. This level involves the Nadir, Sunside, Antisunside, Leading side and the Zenith with all the internal components attached. The lagging side will be integrated last as it has minimal connection coming to it. Electrical routing is done for each panel as it is assembled and testing of the connection undertaken immediately.

3. Level 3

Level 3 involves with integrating all the external surface components like the monopole antennae and the puck antenna. All the electrical routing is completed at this level.

4. Level 4

This level involves integration of the Solar Panels and the Sunsensors. The integration of these parts was delayed as long as possible as they are sensitive and susceptible to handling damage. Multi-layer insulation is applied onto the panels prior to fixing on the solar panels as per thermal design requirements. The wiring of the solar panels and the cables connecting to the Lagging side is done at this stage.

5. Level 5

This level includes finishing the satellite assembly by integrating the Lagging panel to close the cube. Thermal protection that is to be done post satellite integration will be done at this level.

The sequence developed for Pratham has the following major steps –

- Use the Mock Launch Vehicle Interface (attached on the nadir) as the support for all the integration steps.
- Integrate the Nadir, Sunside, Antisun side simultaneously.
- Integrate the Leading side
- Integrate the Zenith side
- Hold the Lagging side parallel to the Nadir at the Zenith-Lagging edge. Using this edge as the hinge for the wires. Finish the wiring on the Lagging side.

The rationale behind this solution was:

- Nadir must be used as the base as it is the strongest of all sides and will easily bear the load of the other sides. Also the Mock LVI attached to the Nadir can act as an ideal support to clamp the structure.

- Lagging has the minimal number of electrical connections among the other panels and hence can be attached last.
- To ensure minimal stresses during fastening, the opposite sides of Antisun side and Sunside are attached simultaneously. This is followed by Leading and finally Zenith panels to ensure adequate support for all panels.
- The major problem in integration is that of closing a cube from the outside, while at the same time having electrical connections of correct lengths made on the inside with other panels. This is solved using the principle that rotation in a circular arc preserves the lengths of all radial lines originating at and perpendicular to the rotation axis. The wire routing scheme ensures that no wires are routed from one panel to another crossing the Lagging side. All connections emanating from the Lagging side are routed across the Lagging-Zenith edge. The Lagging panel is swung in an arc around this edge to close the cube. The wires all being radial lines perpendicular to the edge have their lengths preserved before and after closing the cube.

C. Virtual Integration Sequence

It is necessary to validate the integration sequence before it is applied to integration of the Flight Model, to avoid mismatches, overlapping and problems of non-reachability of certain parts. Applying it to another physical model would be expensive and time consuming. It was decided to verify the sequence by animating each of the steps in order on a software model, which helps in identifying problems prior to implementation on the actual satellite, thus avoiding any potential damage to the satellite. The animation is visual proof of the fact that the integration sequence is effective in assembling the satellite and can be followed in reverse to disassemble it, and plays a crucial role in communicating the details of the integration sequence most effectively.

VI. TESTING

In the ‘V-model’ approach, going up the ascending arm stands for the integration of designed and fabricated individual subsystem one by one. For Pratham this testing is divided into three Levels. For each subsystem it is implemented differently, yet the central concept remains the same. Level one test is designed to verify whether a subsystem complies with the Subsystem requirements. The second level tests are designed to check compatibility with all other subsystems an individual subsystem is interacting with. The third and the final level of test are performed on the integrated satellite.

A. Level I Testing

Fabricated circuit boards are checked for connectivity. When all connectivity checks are completed the circuit board is Powered up. All VCC and Ground connections are verified again. Thereafter, the outputs of Voltage regulators that supply Power to the rest of the subsystems are checked for the range of un-regulated voltage expected to occur.

All IC used on-board are checked for individual functionality. The current limiters are connected across variable resistances and tested for operation in the various current ranges expected to occur, all with a safety factor of 1.5. The battery protection IC are connected to the Engineering model batteries and made to charge and discharge, and the cut-off limits are verified.

As the last test for Level I for Power subsystem, the Microcontroller is programmed and tested for detecting the SNAP signal (detection of launch), Detection of over-current and Health-monitoring data gathering.

B. Level II Testing

The electrical subsystems after they have passed the the level one tests are tested for compatibility with each other. This forms the Level 2 testing for the electrical subsystems. For Pratham we plan to do it in three phases. For the first phase the On-Board computer (OBC) hardware is run in loop with a real-time environment simulator. For the second phase the Power subsystem hardware is also added to the setup, and for the third and final phase of Level 2 testing Communication Hardware is added. Details of the three phases are as follows:

Phase 1: Running the On-Board Computer in loop with a real-time environment simulator. Phase 1 tests aim to check the proper working of the control tasks of the OBC. The sensor inputs generated by the Environment propagator are Sunsensor values; GPS values; and Magnetometer. To generate these sensor outputs the simulator uses the velocity of the satellite; the angular rates; position in space, and attitudes as the state variables. The additional information that the simulator uses is the IGRF model for magnetic field of the earth, and the SGP propagator for propagation of orbit. Using the state variables and the models the sensor outputs are calculated and given out through a data acquisition card. These inputs are read by the OBC hardware, processed appropriately and Pulse Width Modulated (PWM) output is generated. The environment simulator reads the PWM and converts it to control torque. This control torque in turn, along with the other disturbance torques is used to propagate the attitude.

Phase 2: On-board computer and the Power subsystem in loop with the real-time environment simulator, the engineering model battery pack and a power source acting as the solar panels. Phase 2 tests target the OBC-Power communication, and the Power board microcontroller functioning, the environment simulator runs as in Phase 1. The Power subsystem is given different inputs according to different operational scenarios; the response of the subsystem is logged by the OBC as Health monitoring data.

Phase 3: On-board computer, Power subsystem and the Communication subsystem in loop with the environment simulator, real battery pack, a power source acting as solar panel and a receiver module for receiving the transmitted data.

Phase three tests attempt to verify the communication channels of the satellite. The data collected via the telemetry channel will be verified against the actual values on-board. This is the final phase of electrical testing for the satellite, after which the electrical subsystems will be cleared for Level 3 testing.

C. Level 3

When the Satellite is integrated, it needs successfully pass a couple of tests before it can be launched. The satellite is made to undergo hot-cold test, where the temperature of the satellite is oscillated between the two extremes. This is followed by thermovacuum test, where the hot-cold test is repeated in vacuum environment of approximately 10^{-5} torr. On the mechanical front, the satellite is bolted to a vibration table and made to undergo vibration loads similar to the launch loads. All these tests have certain specified levels for the Qualification Model and the Flight Model, and the QM levels are slightly harsher.

VII. TRANSPORTATION

Transportation box is used as safe enclosure for carrying satellite between various stations on ground during various occasions for different tests before it is launched. The first concern before designing transportation box is to decide the mode of travel (Air, Train or Road). Considering the loads and handling procedures, air transportation is finalised as the mode of transportation.

The main objective of transportation box is to provide vibration isolation, humidity level control, air tightness, ESD protection and clean environment for the satellite.

The transportation box for Pratham is a rectangular plywood box with foam filled inside. And the foam shape at the base is female projection of the satellite nadir face along with LVI system. This will ensure snug fit and corner blocks of foam are placed at the bottom all the other four corners of the top.

Figure 4: Transportation Box

Loads considered in design are given below:

Approximate Horizontal and Vertical loads (harmonic load): 1g at 3-10 Hz. Impulse loads are acted on the box whenever vehicle hits the bumps or sudden fall of box from a height.

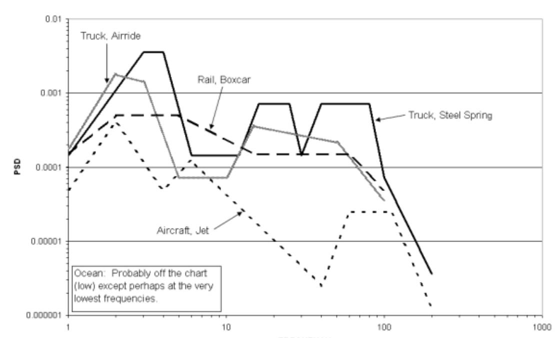

Figure 5: Random vibration load data during transportation.

Structural limits: Maximum displacement between 5 to 10 Hz should not exceed 8 mm and between 10 to 100 Hz acceleration should not exceed 3.75 g.

Humidity control: Typically the humidity levels in India are 40-70%. The satellite structure will be safe below 50%. Excessive humidity can lead to corrosion of Al 6000 series metals. Hence humidity level control is an important factor. Typical desiccant silica gel in calculated amount is used to achieve this. Typically 2 kg/m^3 of silica gel is used. As per this our transportation box (0.25 m^3) requires 500 grams of silica gel (Rapid gel). It has to be replaced every 90 days. Marine plywood is used for construction due to its waterproof properties.

ESD protection: Aluminium foils are placed on all the inner faces of the transportation box and electrical connection with satellite is always maintained through copper strip connection. This is in turn connected to another strip outside the box which is always grounded in some way.

Thermal Considerations: Typical temperature range in India is 20^0C to 41^0C. All the satellite components are designed for temperature range of -40^0C to 80^0C. In India, it is very unlikely for the transportation box and inside satellite to go out of this range hence no extra protection is needed in this regard.

Sun mica sheets: Sun mica sheets are pasted on outside surface of wooden box so that splintering of ply wood when rubbed against rough floor surfaces is avoided.

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