

# Simulator for Functional Verification and Validation of a Nanosatellite

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*Abstract* - The introduction of CubeSats in the space industry has opened the frontiers of space to educational institutions. This surge of new organizations in the industry calls for a better process to test and validate the operations of a satellite before it is launched. The process should be flexible to include a variety of payload and should be compatible with the existing popular systems in the industry. The paper discusses one such process devised by the members of Team Anant, the Student Satellite Team of BITS Pilani.

The team is currently working on a 3U nanosatellite with a hyperspectral camera as its primary payload. Being a research-based project, the members developed a Satellite Simulator by themselves rather than utilizing similar platforms for the validation of their satellite's operation. Apart from the various modules present in any general satellite, the program offers the utility of adding an independent Operations module, specific to the interests of the user. The user can then easily program the planned FSM of the modes of operation of their satellite and use the developed platform to perform tests comprising the satellite's hardware as well as software-logic. The program has been developed in MATLAB, making it convenient as well as economical to integrate it with hardware for a Hardware-in-loop (HIL) simulation. The program is essentially a virtual replica of the actual space environment experienced by the satellite with the ability to generate 3D visualizations of the satellite in orbit.

Currently, processes like HIL simulations are able to accurately determine the response of the satellite independent of any other celestial body in its vicinity. A team can use the developed program in association with the HIL simulation to enhance the accuracy of that process. The Physics module determines the position of the satellite in Earth's orbit and its current attitude. The Telemetry module can estimate how much data can be downlinked/ uplinked during each pass over the ground station, depending on the launch time and location. The Power module is used to estimate the instantaneous power levels of the satellite in each mode of its operation, considering the changing position of the Sun and the satellite's attitude. The program also features a replaceable Payload module, which in our case, replicates the function of the imager.

The modular approach in the development of this program makes it feasible to add more functions depending on the requirement of the project. The use of MATLAB also makes it compatible with most platforms used for testing the operations of a satellite. All aspects of the program can be easily modified according to the various specifications of the satellite, its orbit, and the mission. The program, in collaboration with a hardware-in-loop simulation, is an efficient and accurate way to verify the physical operations of the satellite. The flexibility, compatibility, and accuracy of this process make it a viable alternative to traditional HIL testing.

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## 1. INTRODUCTION

The concept of CubeSats was introduced by CalPoly and Stanford when they released the specifications to promote and develop the skills necessary to build Low Earth Orbit (LEO) based small satellites. Since its introduction in 1999, the concept has gained popularity among educational institutes as well as amateurs scientists.

The surge of new organizations, planning and building CubeSats, calls for a process to validate the operations of a satellite. Team Anant, the Student Satellite Team of Birla Institute of Technology and Science (BITS) Pilani has devised such a process for the 3U satellite it is building. The paper discusses the details of the developed satellite simulator and how it can be effectively used in the development of the satellite flight-plan, by verifying and validating the operations of a satellite before it is launched.

## 2. SIMULATOR STRUCTURE

The Simulator was initially planned and developed to verify the energy balance of the nanosatellite. Further modules were added with time to enhance the capabilities of the simulator. The choice of various notations and reference frames partially reflect the initial methodology behind the whole design process. However, the simulator was always developed in modules to increase its readability.

The program consists of various software functions designed to provide a particular output for a particular set of inputs. As each function models the working of a particular aspect of the satellite, we will refer to them as 'models' in this article. Some basic models also form a basis for more complex

models. A module is not an actual software function, but a group of various models that have similar functionality.

The simulator can be seen as a hierarchal structure of modules, with various modules being used independent of other modules, while other modules being used in close conjunction with other modules. This approach ensures that a module can be updated or debugged without changing other modules

A rough segregation of the various modules in the simulator is as follows:

1. Environment and Forces Module (EFM): To model the environment around the satellite and the external forces acting on the satellite.
2. Orbit Dynamics Module (ODM): To model the path of the satellite in space.
3. Satellite Dynamics Module (SDM): To model the rotation of the satellite around its own center of mass.
4. Components Module (CPM): To model the various components on-board the satellite.
5. Controls Module (CTM): To model the various algorithms used to control the orientation of the satellite.
6. Electrical Power Module (EPM): To model the electrical energy generated and used by the satellite at every instant.
7. Telemetry and Ground Station Module (TGM): To model the pass of the satellite over a predefined ground station location on Earth.
8. Operations Module (OPM): To model the modes of operation of the satellite.
9. Visualization Module (VZM): To visualize the orbit and the ground track of the satellite.
10. Miscellaneous Module: Includes utility models frequently used by various other modules.

The simulator was specifically developed for Team Anant but the modularity of the simulator ensures that, according to a specific mission, more models and modules can be integrated into this simulator in a hassle-free manner without affecting the existing functionalities.

The various modules in the current version of the simulator, along with the models incorporated within the modules, have been discussed in detail in the subsequent sections of this article.

### 3. SIMULATOR MODULES

The simulator has ten modules as described briefly in the last section. Each of the modules has been discussed in this section in detail.

#### *Environment and Force Module: EFM*

The Environment Module emulates the environment that the satellite will experience in space. The force module determines the various forces acting on the satellite in the orbit. The module has been broken into sub-modules, each calculating different forces acting on the satellite independently. The different environment models currently included in the simulator are as follows:

1. Solar Ephemeris Model: The model is used to predict the apparent position of the Sun as seen from the satellite in the Earth Centred Inertial (ECI) reference frame. The model uses the time of deployment of the satellite to estimate the position of Sun in the inertial frame. It then uses the position of the satellite to determine the position of the sun as seen from the satellite. A similar model can be implemented on-board the satellite as well. An Ephemeris Model to estimate the position of Moon has not been implemented on the simulator but can be added if required.
2. Magnetic Field Model: The simulator uses the International Geomagnetic Reference Field (IGRF) Model to estimate the strength and direction of the magnetic field around the satellite (in the inertial frame). The model uses the launch time and the current position of the satellite, to estimate the magnetic field. The simulator also uses the World Magnetic Model in-built in MATLAB for the same, depending on the altitude of the satellite.
3. Albedo Model: The radiation from the sun that falls on the satellite after reflection from the surface of the Earth, is known as Albedo. The model uses the distribution of the reflectivity of Earth, the position of the satellite and the information from the Solar Ephemeris model, to estimate the incident Albedo on the satellite.
4. Outgoing Longwave Radiation (OLR) Model: The Earth radiates energy in the thermal infrared part of the electromagnetic spectrum. The model estimates the OLR near the position of the satellite which, along with albedo and solar radiation, is essential for thermal analysis of the satellite. The model uses the launch time and the current position of the satellite to estimate the OLR around it.

The EFM also consists of various force models which estimate the various minor external forces acting on the satellite due to the environment it is in. The different force models currently included in the simulator are:

1. **Atmospheric Drag Model:** Drag due to the Earth's atmosphere has a noticeable effect on the satellites in Low Earth Orbit. The Drag model uses the satellite's velocity vector, along with the current attitude, to estimate the decelerating force on the satellite due to the atmosphere. It can further be used to determine the drag torque on the satellite.
2. **Radiation Pressure Model:** The radiation incident on the satellite exerts a force on it. The radiation can be sunlight, albedo or OLR. The model uses the environment models and the current attitude of the satellite, and estimates the force on the satellite due to incident radiation. The same force can be used to estimate the radiation torque on the satellite.
3. **Gravity Gradient Model:** Any non-symmetrical object in orbit is subjected to gravitational torque due to the variation of earth's gravitational force onto the object. The model estimates the torque due to this gradient on the satellite. This calculated torque is then used to propagate the dynamics of the satellite.
4. **Magnetic Residue Model:** The various electrical components onboard the satellite might induce an unwanted residual magnetic moment which in turn produces a torque when it interacts with the Earth's magnetic field. The model estimates this torque on the satellite by using the estimated value of the onboard residual magnetic moment.

*Orbit Dynamics Module: ODM*

This module is used to predict the orbital position and velocity (OPV) of the satellite at a specified time. The model takes into account the following forces when determining the coordinates of the satellite:

1. **Gravitational force due to Earth and its oblateness:** Determined using the current position and velocity of the satellite with respect to the Earth.
2. **Gravitational force due to Sun:** Determined using the position of the satellite, and the position of the Sun with respect to the satellite.
3. **External force due to the atmosphere:** Determined using the Atmospheric Drag Model.
4. **External force due to incident radiation:** Determined using the Radiation Pressure Model.

There are two options to choose from, within the ODM. The first option propagates the OPV at a later instance, by using the OPV at the current instance. Given that we can determine the various external forces acting on the satellite, we can linearly propagate the current OPV of the satellite, to estimate the OPV at a later instant in time. To increase the accuracy of the process, the sampling time is divided into multiple

subdivisions and the OPV for each subdivision is calculated sequentially.

The other option uses TLE to determine the current OPV of the satellite. The TLE can be used to determine the current Keplerian orbital elements of the satellite, which can then be used to estimate the position and velocity of the satellite at the instance the TLE was recorded. In this case, either the orbital elements or the OPV can then be propagated to find the OPV at a later instance.

Propagating the orbital elements is complicated and requires higher computational effort as compared to propagating the OPV itself. So the first option is used as the primary option on the simulator. The second option is used to propagate the OPV on-board the satellite, and the developed model thus replicates the actual process being implemented on the satellite.

*Satellite Dynamics Module: SDM*

The SDM is responsible to determine the angular velocity and the attitude of the satellite at any particular time. The module has two major tasks to be done:

1. **Angular Velocity Propagation:** The angular velocity of the satellite can be assumed or fixed at the start of the simulation. Due to the various forces acting on the satellite, the angular velocity will change with time. SDM is responsible to determine the angular velocity of the satellite at all instances of time. SDM is similar to ODM in this respect.
2. **Attitude Quaternion Propagation:** The orientation of the satellite after deployment is fixed at the start of the simulation. Due to the angular velocity, the orientation of the satellite changes continuously. SDM is also responsible to determine the orientation of the satellite by propagating it, similar to OPV and the angular velocity.

Just as ODM is used to determine the position and velocity of the satellite in space, SDM is used to determine the attitude and angular velocity of the satellite w.r.t. its center of mass. The two modules work independent of each other and require inputs from just the EFM. The SDM is also used in verifying the control algorithms for the satellite. SDM acts like the system and the actuator models act as the controllers for the system.

*Component Module: CPM*

The CPM basically includes all the major components used onboard that can affect the satellite. Two components actually affect the orientation of the satellite and are modeled in detail:

1. **The Magnetorquer:** The magnetorquers module takes into account the various properties of a torquer to estimate the actuation it will provide for different values of current. The parameters can determine the

magnetic moment produced by the torquer, which can be used to determine the torque it produces on the satellite. The SDM can then be used to estimate the effect of that torque on the satellite.

2. The Reaction Wheel: The reaction wheel model works similar to the magnetorquer model. Given the parameters of the wheel and the relative position of the wheel w.r.t. the center of mass of the satellite, one can estimate the torque on the satellite due to the wheel. The SDM can then be used to estimate the effect of that torque on the satellite.

The choice of the components modeled in detail was based on the actuators being used by Team Anant. The modular approach of the CPM ensures that a user can easily add more actuators to the simulator without any effect on any other module.

Other components of the CPM did not affect the satellite or its orientation, but were essential for verifying the operations of the satellite. Some of these components include:

1. Magnetometer: We can assume that the Magnetic Field Model of the EFM provides us with the true magnetic field around the satellite in orbit. The magnetic field sensors onboard the satellite will then sense those true values and provide us a measured magnetic field. The magnetometer model has been designed to take in the true magnetic field values and introduce a random error to it. The sensor can be more accurately modeled and added to the simulator separately. The model can be used to test the Attitude Determination System of the satellite simultaneously with the modes of operation.
2. Hyper-Spectral Imager: The imager was not modeled in detail and was only used to estimate the power used by the payload onboard the satellite. The same Imager model is also used to estimate the data that has been downlinked to the ground station after each satellite pass.
3. Power Extensive Components: Each of the various components that use a major chunk of power has been modeled to estimate the power used by them in a particular amount of time. The estimated power from the components is then used to verify the operations of the satellite. [1]

#### *Controls Module: CTM*

This module comprises of the various control algorithms that will be implemented on board the satellite. The simulator can effectively be used as a software testbed to test the control algorithms as well. Once the control algorithms are fixed, they are used to verify the operations of the satellite.

The control module has various algorithms used at different phases of the mission lifetime. The module has separate models for detumbling, pointing and tracking. Each of them

has different actuators being used and each of them has different power requirements. The three models can be independently developed and modified as per the mission. Other control models and actuator models can be designed and added to the simulator as per the requirement.

#### *Electrical Power Module: EPM*

The EPM is used to estimate the current energy level of the satellite. There are two processes going on in the module:

1. Energy Generation: This model uses the position of the sun, the attitude of the satellite, and the dimensions of the solar cells, to find the energy incident on each face of the satellite. The time average of this energy will give the average power incident on the solar cells. We can then use the known/estimated values of the efficiency of solar panels and that of the electrical power components to find the average power delivered to the electrical power system.
2. Energy Usage: Depending on the current mode of operation, different components of the satellite will be using the energy for different periods of time. The Energy Usage model finds out the amount of energy that is currently being used by each component.

The module also incorporates eclipse mode when the incident energy is assumed to be zero on all faces. The condition for eclipse is found geometrically and is checked at every time step before the incident energy is stored. Energy generated due to albedo is also included in the module along with the energy generated directly through sunlight

#### *Telemetry and Ground Station Module: TGM*

The TGM module is used to model the movement of the ground station with respect to the satellite. The working of the TGM can further be divided into two sub-modules:

1. Ground Station Model: This model is used to determine the position of the ground station in the Earth Centered Inertial (ECI) frame. As the Earth rotates, the position of the ground station will change as well. The model uses the launch time, and the coordinates of the Ground Station to determine its position.
2. Satellite Pass Model: The model uses the position and velocity of the satellite at a specified instance to calculate the following parameters as seen from the primary ground station, in the appropriate reference frame:
  - a. Azimuth of the satellite: The clockwise angular distance of the position of the satellite from the North direction.

- b. Elevation of the satellite: The angular distance of the satellite from the horizon.
- c. Straight line range of the satellite: The distance a communication signal will travel through the atmosphere.

The Azimuth and Elevation can be used to test the capabilities of a ground station. The module is used to estimate the pass time of the satellite over a particular ground station. A similar model to estimate the occurrence of the pass as well as the estimated pass time can be used on-board the satellite.

The elevation and the range of the satellite can be used to estimate the error in the communication signal, once received at the ground station.

The TGM assumes that the maximum angle of visibility for the satellite can be  $160^\circ$  for the ground station to communicate with it. That means that the satellite needs to be at least  $10^\circ$  above the horizon for effective communication. The value can be changed if required.

*Operations Module: (OPM)*

The satellite, over its time in space, must autonomously switch between various states, each state being determined by the tasks that the satellite is performing and the external and internal stimuli it is exposed to. We call these states ‘modes of the satellite’. Switching between different modes is an important part of mission planning and can alter how reliable a satellite’s operation is.

The various modules defined till now have been used to model the various properties of the satellite once in orbit. The OPM is developed to use those parameters and model the transition of modes of the satellite during its operation. Since the simulator effectively imitates the situation in space, it can be used to both develop the modes as well as to verify them.

To develop the modes, the various conditions for transitioning between any two modes is expressed in terms of the various parameters about the satellite. The conditions are then used to determine new parameters about the satellite and

the new parameters are then iteratively used to define new and more robust transition conditions. This helps the user fine-tune the parameters and figure out changes that should be made in the design to allow the satellite to perform requisite operations.

To verify the operations of the satellite, the designed conditions for transition can be modeled in the OPM along with all known parameters. The conditions are assumed to be exhaustive. The transition of the states and the various parameters at each transition is noted and studied. Since the simulator can model all possible disturbances and physical emergency cases on the satellite, it can also be used to test the sequence of operation of the satellite in all those cases. The various parameters at the transition are then compared to the known parameters to verify the intended operation.

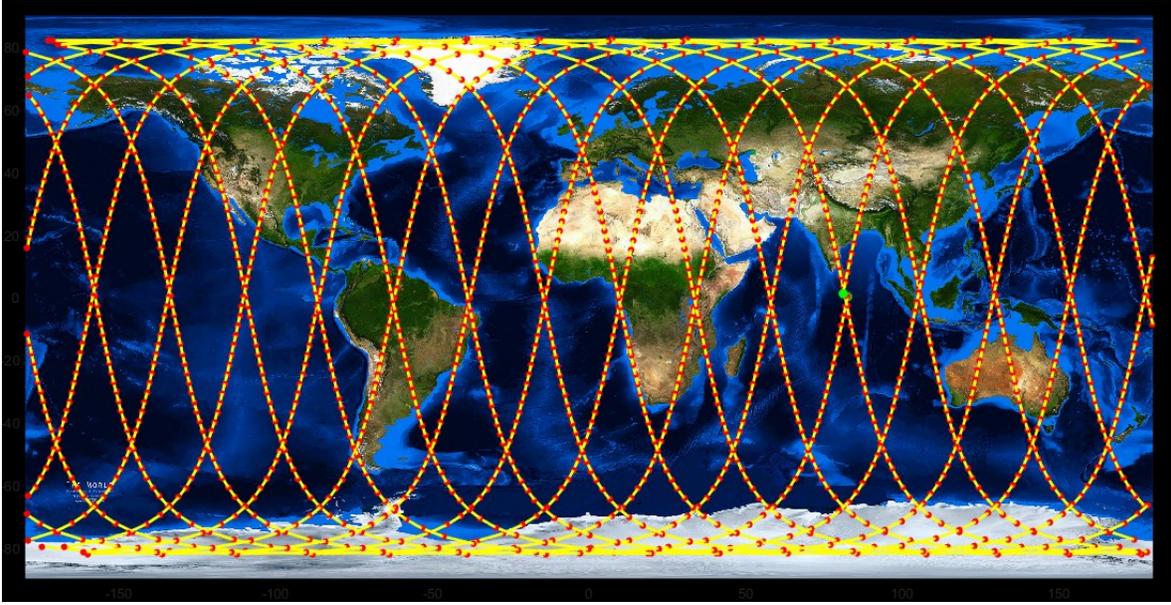
*Visualization Module: VZM*

Along with modeling the various parameters of the satellite, the simulator also includes a Visualization module to augment the process of verifying the operations. The module consists of two models:

1. Satellite Visualization Model: The model uses the OPV to trace the orbit path of the satellite around the Earth. It also uses the position of the Sun to illuminate the Earth at exactly the realistic condition and incidence so that the issue of eclipse and sun-lit regions can be easily visualized. Figure 1 shows a sample image from the simulator for the proposed orbit for Team Anant.
2. Ground Track Model: A model for ground track visualization has been developed to easily understand the expected ground track of the satellite over time. The same can be used to plan imaging areas and location of secondary ground stations. It can also be used along with OPM to verify the operations of the satellite when above a ground station or an imaging area. The model uses the time of deployment and the OPV to find the point directly below the satellite on a Mercator projection of the surface of the Earth. The determined ground track for 15 orbits of a LEO satellite is shown in figure 2.



**Figure 1: Orbit Visualization for a LEO Satellite**



**Figure 2: Ground Track for a LEO Satellite**

### Miscellaneous Module

Certain models in the simulator do not fall in any of the defined modules. These models are not innately used in the simulator but are used to design several other models. These include:

1. Rotation and Quaternion Model: To model the rotation of a 3D object using quaternion geometry.
2. Incidence Model: To model a radiation incident on a particular area.
3. Coordinates Model: To determine the coordinates of the satellite provided the OPV and time of deployment.
4. FOV Model: To determine the Field of View (FOV) of the satellite when at a particular point in orbit.

## 4. SIMULATOR OPERATIONS

As described earlier, the simulator has been designed in a user-friendly manner. The following section describes the properties of the simulator that make it an ideal setup to test and verify the operations of a satellite along with Hardware-in-loop (HIL) testing.

### Modularity

The modular approach ensures that new modules can be added to the simulator as per the requirement of the user. The modules can be independently developed or use the models developed in the Miscellaneous module. Separate modules can be added to integrate the simulator with proposed hardware for in-loop testing. The modularity is also convenient when calibrating or debugging the designed models.

### Generalization

The only constants used in the simulator are given below in Table 1.

**Table 1: General constants used in the Simulator**

Constant	Value	Dimensions
Universal Gravitational Constant	6.67428E-11	$m^3kg^{-1}s^{-2}$
Speed of Light	299792458	$m/s$
Astronomical Unit	1.496E11	$m$
Mass of Sun	1.989E30	$kg$
Intensity of Sun (Solar Constant)	1361	$W/m^2$
Mass of Earth	5.972E24	$kg$
Radius of Earth	6378000	$m$
Angular Velocity of Earth	7.29E-05	$rad/s$
J2 Perturbation Coefficient	1.082E-3	—

Every other parameter of the satellite can be modified according to the mission requirement of the user. This includes:

1. Mass, Centre of mass and Moment of Inertia tensor of the satellite.
2. Time and geographical coordinates of deployment of the Satellite.
3. Initial Keplerian orbital elements of the satellite.
4. Geographical coordinates of the Ground Station.

5. Solar Panel Area in different axes of the satellite
6. Efficiency of the solar panels and the power supply electronics.
7. Components of the satellite and their power requirements.
8. Control algorithms for de-tumbling, pointing and tracking.
9. Modes of Operations of the satellite.

The simulator can effectively be treated as a custom-built software for a satellite without losing its generality. This increases its utility by making sure that it can be used for any satellite without much inconvenience.

The presence of models for Sun, albedo and OLR also makes it convenient to use the simulator for thermal analysis of the satellite.

#### *Integration*

The simulator has been developed in MATLAB. The choice of the development environment makes it compatible with most platforms used for testing the operations of a satellite. The use of MATLAB is also very convenient when integrating it with hardware sensors or micro-processors.

Traditional HIL testing is generally used to test the hardware of the satellite in absence of any other force. Using the simulator along with traditional HIL testing will ensure that the hardware is tested in an accurate model of the satellite's orbit. Also, as the simulator essentially incorporates all aspects of the satellite, multiple hardware components can be tested simultaneously under various cases of normal and emergency operations.

As the simulator models the environment experienced by the satellite, all the sensor values onboard the satellite can be provided by the simulator itself. These values can then be used by a user to test the design of the on-board systems. Also, as the simulator is also an accurate model of the satellite's behavior, any output from an actuator can be fed into the simulator to determine its effect on the satellite.

### **5. CONCLUSION**

The simulator is basically a virtual replica of the satellite as well as the environment it experiences. It is exhaustive in itself, which makes it possible for a user to design and verify the modes of operations of a satellite on it. The simulator can also be used to test the various determination and control algorithms to be implemented on-board the satellite.

Utilizing the satellite's model of the simulator also makes it suitable to test various actuator and other hardware components. The use of MATLAB as the development software makes it easier to integrate the components with the simulator. As the simulator is an accurate description of the

actual conditions in orbit, it can be used along with traditional Hardware-in-Loop testing to increase the accuracy of the process.

The simulator, being developed in modules, has an extremely flexible structure and can be framed to be used for any satellite mission. The inbuilt modules have a general design which can be altered as per requirements. The modularity also makes sure that more modules can be conveniently added to the program whenever necessary.

The program, in collaboration with a hardware-in-loop simulation, is an efficient and accurate way to verify the physical as well as software operations of the satellite. The flexibility, compatibility, and accuracy of this process also make it a viable alternative to traditional HIL testing.

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## BIOGRAPHY



**Tushar Goyal** is set to receive a B.E. (Hons.) in Electrical and Electronics Engineering from Birla Institute of Technology and Science, Pilani, India in 2019. He has been with Team Anant since January 2016. He has been the student coordinator for the team since March 2017, managing the administrative and financial aspects of the team. Prior to that, he was the subsystem lead for Attitude Determination and Control System (ADCS) of the team. The ADCS is responsible for developing algorithms to determine the orientation of the satellite and then control it according to the requirements. His interests lie in Astrodynamics and Mission Analysis and he aspires to pursue research, in the same field, in the future.



**Kushagra Aggarwal**, a student of Birla Institute of Technology and Science, Pilani, India is pursuing B.E. (Hons.) in Electronics and Instrumentation Engineering. He was a part of Team Anant from August 2016 to May 2018 contributing to the development of Onboard Computer subsystem. He also served as the System Engineer for the team and played an important role in developing the modes of operation of the satellite. He was a Research Intern for Summer 2018 at the University of Tokyo and is currently a research scholar at IRISA, France. His interest lies in the field of device physics and quantum computing.