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SENSUS: a Multi-Physical Satellite Simulation Platform with Applications to Space Cybersecurity and Space Weather Research

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Abstract

This paper presents SENSUS, a multi-physical satellite simulator developed using MATLAB, Simulink, and Simscape. It models key spacecraft subsystems: AOCS, thermal, EPS, propulsion, OBC, TT&C and communication channel, and their interactions with the space environment. The platform simulates physical effects such as radiation, orbital perturbations, and thermal fluxes, while enabling fault injection linked to space weather and cybersecurity threats. By integrating diverse physical domains into a cohesive simulation, SENSUS provides a high-fidelity modular tool for simulation exercises in realistic mission scenarios.

1. Introduction

Space systems are essential to daily life on Earth, as they enable crucial assets such as communication, navigation, TV broadcasting and environmental monitoring. Their increasing complexity demands continuous innovation, testing, and predictive analysis, but full-scale satellite replicas are costly and time-consuming to built; thus, space actors extensively rely on high-fidelity simulation platforms that reproduce space system modules and their interactions. Along with the apparent cost-effectiveness, this modeling and simulation paradigm improves design reliability and efficiency.[6]

This paper introduces SENSUS, a satellite simulator that integrates diverse physical domains into a unified simulation, serving as a high-fidelity, modular tool for realistic mission scenario exercises. Based on a combination of MATLAB, Simulink, and Simscape, the simulator comprises two parts: the environment and the spacecraft. The physical environment simulator is in charge of simulating all the effects related to the space environment, from orbital perturbation, to the computation of disturbance forces and eclipse conditions. The satellite simulator is a multi-physical model of the spacecraft itself, and it reproduces the most important subsystems and their interaction. The simulation includes the AOCS subsystem, a thermal model of the satellite, the OBC monitoring the subsystems and managing the satellite operative modes, power generation and distribution, and the propulsion subsystem. Telemetry and telecommands are sent to the ground station configured for the scenario. The satellite platform is highly configurable.

In addition to the nominal behavior of the components, a set of anomalies related to major space weather and cybersecurity threats is implemented in the model. As space exploration expands, so does the danger of cyberattacks on space systems.[4] Given the potential effects on national security, public safety, and the global economy, it is essential to prioritize cybersecurity from the design phase of space systems. Accurate software models of critical infrastructures can be used in the framework of cyber-ranges to assess responses to cyber-attacks and failures. In this direction, space cybersecurity research will highly benefit from simulation platforms that include all satellite components and the space environments, and that can be integrated as underlying platforms within the architecture of a cyber-range. Satellites face environmental hazards related to space weather, from radiation to possible collisions with space debris. These threats can easily lead to subsystem failures, mission degradation, and even total functionality loss.[9] Cybersecurity and space weather threats ultimately lead to a set of anomalies that have similar effects on satellites. However, despite the major effects that these faults can trigger, their modeling is often neglected in simulations. SENSUS tries to bridge the gap within satellite simulations, space weather and cybersecurity research.

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2. Satellite Environment and Subsystem Simulator

SENSUS, short for Satellite Environment and Subsystem Simulator is a multi-physical satellite simulation platform developed in Matlab, Simulink, and Simscape. It is composed of detailed models of all the key satellite subsystems, namely AOCS, thermal, EPS, propulsion, OBC, and TT&C / communication channel from and to the ground station, and a model of the external environment. The simulator is highly modular and configurable, leveraging both causal and a-causal modeling paradigms depending on the subsystem requirements. Figure 1 shows a simplified yet complete view of the simulator architecture. The physical environment part models perturbed orbital propagation, computes all the relevant environmental forces and torques acting on the satellite, and returns important physical information such as the intensity of geomagnetic field and eclipses. The satellite model is configurable in terms of geometry, materials, solar array properties, and onboard components. The Attitude and Orbital Control Subsystem (AOCS) estimates the satellite attitude by processing sensor data that reproduce real hardware errors and noises, and applies different control laws through modeled actuators, supporting detumbling, slew maneuvers, and 3-axis pointing. The Thermal subsystem (THM) simulates temperature dynamics from radiative and conductive heat transfer based on material properties. The Onboard Computer (OBC) is implemented in Stateflow as a finite state machine, and manages the satellite operational modes. The Electrical Power Subsystem (EPS) models generation, storage, and distribution, accounting for solar panel output and battery behavior across orbital conditions. Finally, the Telemetry and Telecommands (TT&C) and Communication (COM) blocks models signal transmission and reception from and to the ground station, considering atmospheric propagation losses and ground station access.

The focus on capturing subsystem interdependencies yields the possibility of simulating realistic system-level behavior under nominal and anomalous conditions caused by space weather and cybersecurity threats. The architecture diagram also highlights the main connections to Space Weather threats, represented by specific events or impact with Micrometeoroids and Orbital debris (MMOD). Cybersecurity threats on the communication channel are triggered from a malicious ground station, and can escalate up to the satellite subsystems. The following sections of this paper present a more detailed description of modules and components.

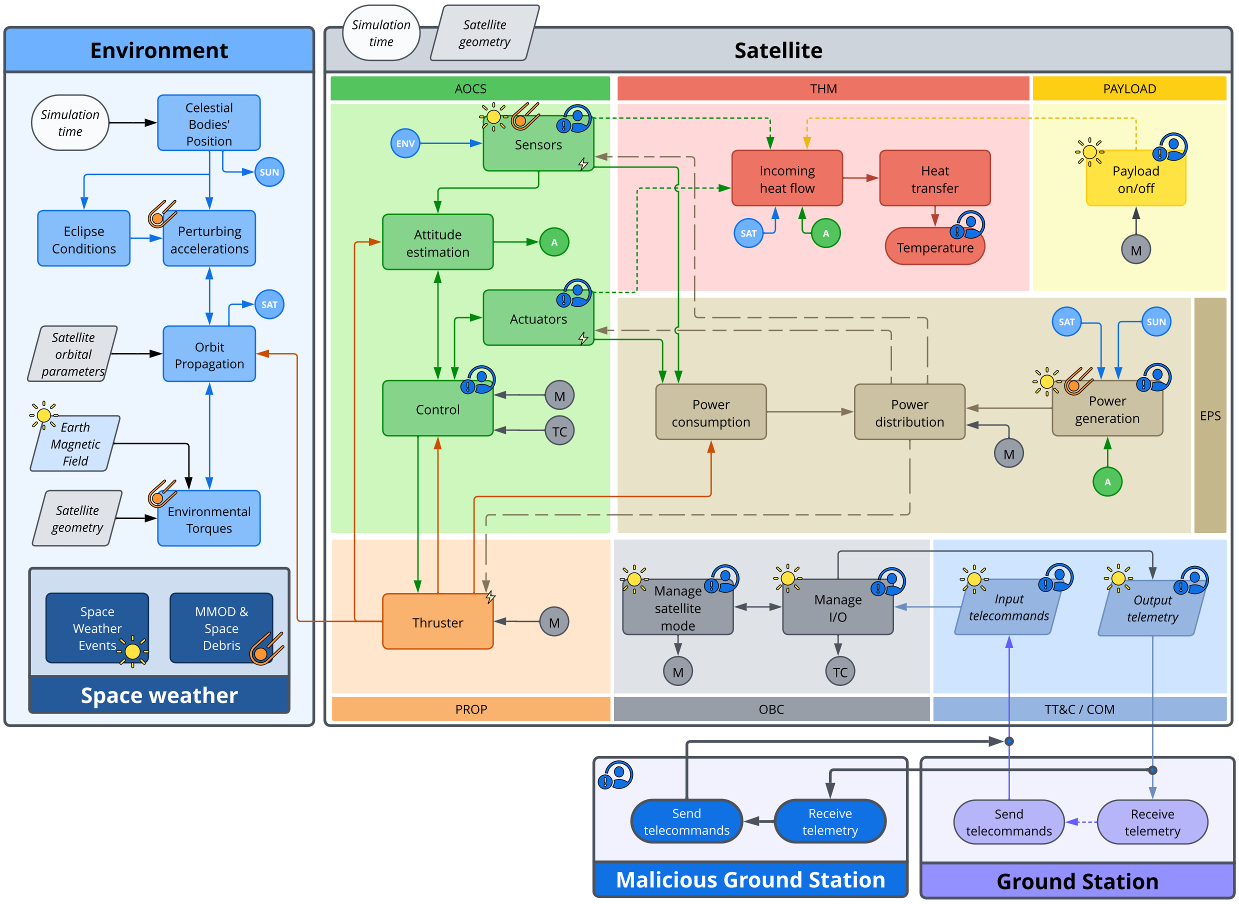

Figure 1: Schematic view of SENSUS overall architecture

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2.1 Physical Environment simulator

The Physical Environment model computes all the information influencing the satellite orbit throughout the simulation. simulation module defines the physical parameters influencing the behavior of the satellite during the orbital phase. It continuously interact with the satellite model to relay relevant events and affect its operations accordingly.
The following parameters need to be configured to tailor the simulation to specific missions:

- **Satellite orbit**: the nominal orbit of the satellite is selected before the simulation starts, by specifying the orbital starting point by either a set of keplerian parameters, or the initial satellite state in terms of position and velocity. In this second case, the information on the reference system is also required.
- **Initial epoch**: the information on starting date and time are required to precisely retrieve the position of celestial bodies considered in the simulation, Earth, Sun and Moon.

The model accomplishes varius tasks. A summary of the most important ones is presented here:

1. **Celestial bodies' position**: returns Earth, Moon and Sun's position at each simulation time. Data are retrieved from ephemeris in Earth-centered reference frame, considering the elapsed time interval starting from the configured initial epoch, and then used to determine the satellite-to-body position vectors.
2. **Orbit propagation**: computes the position and velocity of the satellite by propagating the orbit at each simulation time, considering the most relevant perturbing accelerations given the orbital regime. Orbital propagation follows Eq. 1, where $\ddot{\boldsymbol{r}}$ is the satellite acceleration, $\boldsymbol{r}$ is the satellite state, μ is the Earth gravitational constant, and $\boldsymbol{p}$ is the vector of the overall perturbing acceleration:

   $$\ddot{\mathbf{r}} = -\mu \frac{\mathbf{r}}{r^3} + \mathbf{p} \tag{1}$$

3. **Perturbing accelerations**: computes the perturbing accelerations that modify the satellite orbit. The intensity of the perturbations changes with the orbit regime. The modeled perturbation are atmospheric drag, solar radiation pressure, Earth oblateness and third body effect due to the solar and lunar gravity fields.
4. **Environmental torques**: computes external forces and torques acting on the satellite. It includes interaction with geomagnetic field, Earth J2 effect, solar radiation pressure and atmospheric drag. The magnetic disturbance torque is caused by the interaction between Earth's magnetic field and the residual magnetic induction due to on-board electronic components. In the definition of forces and torques, the satellite rigid geometry and attitude are considered. Perturbing forces are computed for each satellite face, considering the geometric center of the panel as the acting point, and then summed up to obtain the overall effect acting on the satellite center of gravity (CoG). The disturbing torque is computed as:

   $$\boldsymbol{M} = \sum \boldsymbol{r}_i \wedge \boldsymbol{F}_i \tag{2}$$

   where $\boldsymbol{r}_i$ is the position of the geometrical center of the plate with respect to the body's CG, and $\boldsymbol{F}_i$ is the force vector applied to the center of each panel.
5. **Earth magnetic field**: computes the intensity and direction of the geomagnetic field given the satellite position. The magnetic field can be approximated through a dipole model or computed using a more refined models up to order 13.
6. **Eclipse conditions**: computes the eclipse condition of the overall satellite. The subsystem implements a cylindrical model and only considers solar eclipse caused by Earth shadowing. During eclipse phases, effects due to solar radiation are not considered.
7. **Space Weather**: the block reproduces the effect of two of the major space weather actors posing a threat to satellites: solar flares and micrometeoroids. Solar flares are modeled with a probability of occurrence that varies with solar flare intensity. They generate interference on communications and modify the solar irradiance vector. Micrometeoroids can have different mass and diameter, and impact location is selected randomly. When the object impacts on the satellite, it creates a translational and rotational disturbance. If the impact happens on solar panels, the power generated is decreased.

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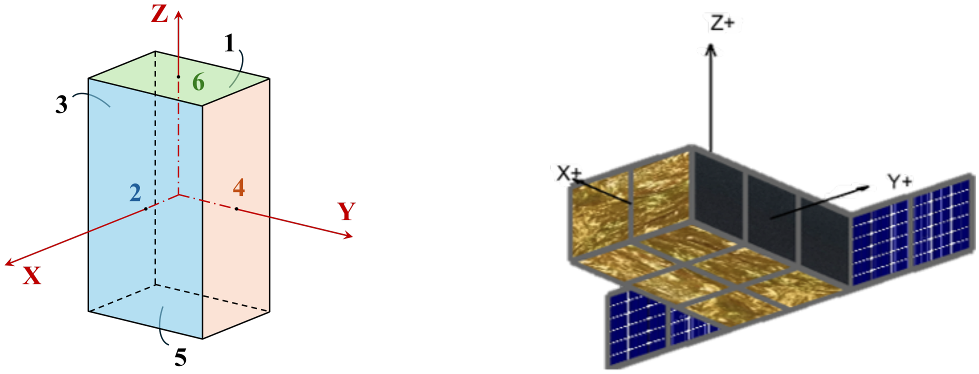
2.2 Satellite general configuration

Before starting any simulation, the satellite need to be configured in terms of:

- **Geometrical properties**: the dimensions and mass of the satellite need to be specified before simulation start. Dimensions are specified along the three orthogonal directions, X,Y,Z of a reference frame centered in the satellite geometrical center. For simplicity, the satellite is considered symmetrical with respect to the reference frame. Satellite mass is specified in terms of absolute value and mass distribution across payload and structural panels.
- **Material of each satellite face**: the material of the external part of each face can be specified choosing among three types of coatings (white, black, gold), solar cell, radiator, or multilayer insulator. Specifying the material also set the optical and thermal properties of the panel.
- **Configuration of deployable solar arrays**: if the satellite is equipped with a set of deployable solar arrays, their number and position and orientation must be specified before the simulation start, since they contribute in the overall estimation of disturbance forces and torques. Moreover, the presence of a solar array drive mechanism also needs to be specified at this stage.

Figure 2(a) depicts a schematic view of the satellite reference frame X,Y,Z centered in the geometrical center, and shows the default numbering of the faces that is used throughout the configuration process. Figure 2(b) present an example configuration with gold and black coatings and two deployable solar arrays aligned along the Y satellite axis.



(a)

(b)

Figure 2: (a) Satellite schematic view and (b) Example of satellite configuration

2.3 Attitude and Orbital Control Subsystem

The Attitude and Orbital Control Subsystem (AOCS) of a satellite is dedicated to the estimation and correction the satellite pose, and to perform corrective orbital manoeuvres. Before the starting of the simulation, some characteristics need to be configured:

- **Onboard sensors**: the available sensor suite comprises Sun sensors, magnetometer, Earth horizon sensor, star trackers and inertial measurement unit. For every sensor that is present in the satellite, the user need to specify position, orientation and technical characteristics.
- **Onboard actuators**: the available actuators suite comprises reaction wheels, control moment gyroscopes, magnetorquers and reaction control thrusters. Similarly to the sensors setting step, the technical characteristics and configuration of actuators need to be specified.
- **Attitude control**: the simulator supports four attitude modes: detumbling, slew maneuvering, fine pointing and no control. The sequence of attitude modes can be configured. If no configuration information is given, the default attitude control performs detumbling followed by a slew maneuver and 3-axis pointing.
- **Reference attitude profile**: during the 3-axis pointing phase, a reference attitude profile need to be selected. The simulator supports alignment to inertial ICRF frame, Sun pointing, Local Vertical Local Horizontal reference frame or custom pointing.

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After the simulation starts, information coming from sensors are processed to obtain an estimation of the satellite attitude, which is in turn used to maintain the desired pointing by exploiting the onboard actuators. SENSUS sensors library comprises Sun sensors, magnetometer, Earth horizon sensor, star trackers and inertial measurement unit. Modelled actuators are reaction wheels, control moment gyroscopes, magnetorquers and reaction control thrusters. The attitude available attitude profiles are: no control, detumbling, slew maneuver and 3-axis pointing. The spacecraft is modeled as a rigid body.

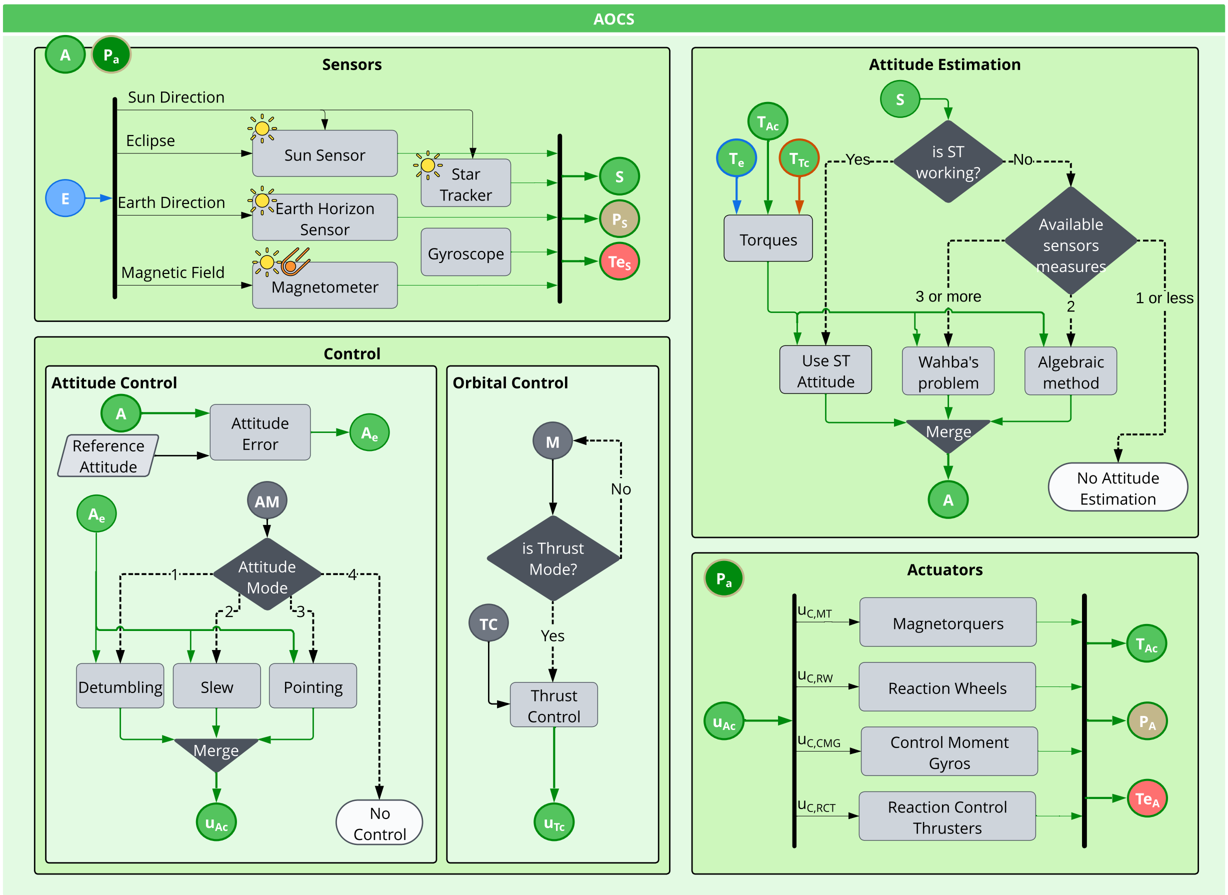

Figure 3: AOCS architecture

1. **Sensors**: for the sake of generality, Figure 3 shows all the available onboard sensors. However, the actual onboard sensors can be defined in the configuration phase. **Sun sensors** detect incident sunlight direction based on light intensity on photodiodes. **Magnetometers** measure the intensity and direction of the geomagnetic field using magnetic flux sensors. **Earth horizon sensors** measure infrared radiation contrast to identify the Earth's edge and estimate the versor pointing to the center of the planet. **Star trackers** capture star field images and matches them to a star catalog for precise orientation. **Inertial Measurement Unit** (IMU) measures angular velocity and linear acceleration using gyroscopes and accelerometers. Sensors models mimics the output of real onboard sensors by adding noise and uncertainties on the nominal Sun/Earth/magnetic field direction or attitude extracted by sensors. Whenever applicable, a check on the sensor FOV is performed, to ensure that the measurement of interest can actually be extracted in the specific conditions of location and attitude. Noises are usually modelled as Gaussian processes, and a final quantization and resolution step is always applied to measurements.

2. **Attitude estimation**: the satellite attitude is estimates based on the information extracted from modelled sensors. As such, the measure is available with a frequency that is directly dependent on sensors' sample times. The determination of the attitude matrix or quaternion is performed in different ways depending on the availability of sensors measurements. If the star tracker measurement is available, then the attitude retrieved from the sensor is the considered value. If the star tracker is not present or not working, but three or more sensors outputs are available, then the attitude determination algorithm is based on the analytical solution of the Wahba's problem. In case only two sensors are active, a simplest but less precise method is used.

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3. **Actuators**: as for the case of sensors, figure 3 shows all the available onboard actuators, although the configuration step ensures the possibility of selecting the present ones. Though they all mimics the output of real components, their modeling is highly actuators dependent. **Magnetorquers** produces control torque by varying the current in magnetic coils or rods, generating a magnetic moment that interacts with Earth's magnetic field. **Reaction wheels** adjusts satellite attitude by accelerating or decelerating a flywheel, creating a reaction torque through conservation of angular momentum. **Control Moment Gyros** (CMGs) control attitude by gimbaling high-speed spinning rotors, generating large gyroscopic torques through angular momentum vector steering. **Reaction Control Thrusters** change the satellite orientation or position by firing small nozzles that expel gas or propellant, creating controlled thrust impulses.

4. **Attitude and orbital control**: the model has built-in implementation of control logics for detumbling, slew manouvering and pointing, for different actuators. The sequence of attitude modes can be configured. If no configuration information is given, the default attitude control performs detumbling followed by a slew maneuver and 3-axis pointing. **Detumbling** phase reduces residual angular rates after deployment by applying countertorques, typically using magnetorquers or thrusters, to stabilize the satellite. A **slew maneuver** rotates the satellite from one attitude to another by commanding coordinated actuator torques to follow a desired angular trajectory. Finally, **3-axis pointing** maintains precise orientation along all three rotational axes using feedback control to keep the satellite aligned with a fixed reference. The reference attitude profile need to be provided in the configuration phase. Orbital control resorts on thrusters to comply to orital maneuvers commands.

2.4 Thermal Subsystem

The thermal subsystem (THM) reproduces heat transfer between the satellite and the external environment. The center of each panel is a thermal node with thermal capacitance and the heat is transferred via radiation and conduction along the panels. Moreover, a node at the center of the satellite reproduces the payload. The incoming heat flux is computed considering the solar flux and Earth infrared and albedo impacting on each of the surfaces. Panels orientation and eclipse periods are considered. The outcoming heat is radiated towards the deep space. Thermal conductivity, absorption and emittance coefficients are defined according to the selected material. Before the starting of the simulation, some additional thermal characteristics can be configured:

- **Operative temperatures of components**: the maximum and minimum operative temperatures of components can be specified. Component's behavior is flagged as non-nominal whenever the component exits the nominal boundaries.
- **Active thermal components**: the presence of an active thermal component capable of maintaining a themal node within specified thermal boundaries can be selected.

The temperature of each satellite face and solar arrays is monitored through a Simscape-based thermal model. The main tasks that the thermal submodule must simulate are:

1. **Incoming heat flux**: the model computed the heat flux coming from Sun and Earth infrared and albedo radiation. The solar radiation incident on Earth is 1370 W/m^2. Earth's albedo radiation is set to 30% of the solar flux, while the infared portion is 230 W/m^2. The portion of the total flux that is impinging on each surface is estimated considering satellite attitude and eclipse conditions.

2. **Heat transfer**: the center of each satellite panel is a thermal node with thermal capacitance. Moreover, the model includes an additional thermal node representing the center of each deployable solar array, as well as one node for the center of the satellite. Through the simulation, sensors output the temperature of each thermal node, plus the temperature of some other specific components. Heat is transferred to and from the environment via external radiation from and to the Sun, Earth and deep space. Internally, heat is conducted through conduction among adjacent panels and radiation between opposite ones. In case active components are present, a part of the model simulates heat injection or removal from all the specified thermal nodes.

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2.5 Power subsystem

The Electrical Power Subsystem (EPS) manages power generation, storage, regulation, and distribution. It typically uses solar panels to generate electricity, batteries to store energy for eclipse periods, and power electronics to condition and distribute stable voltage to all onboard systems. The simulator presented in this paper requires the configuration of some parameters related to the EPS subsystem:

- **Solar arrays configuration**: the configuration of the deployable solar panels needs to be defined before the simulation starts. The choice of position and orientation has already been described in Section 2.2 , but also the number of cells connected in series and parallel for each panel need to be clarified, as it impact on the power generated by the solar array. Moreover, it is necessary to specify their working mode, which can be either at a constant voltage or Maximum Power Point Tracking (MPPT).

- **Solar cells properties**: the optical and electrical characteristics of the single cell are configured. The list include solar cell area, open circuit voltage, short circuit current, and cell efficiency.

- **Components consumption**: the power consumption need to be clarified for all relevant components, in both working and idle mode. It includes at least sensors, actuators, propulsion system, payload, OBC, and power necessary to enable communication to ground.

- **Battery properties**: if batteries are present, their number and characteristics are configured before simulation start. The list include, but is not limited to, battery capacity, nominal working voltage, initial state of charge (SOC), and charging mode.

The tasks of the EPS subsystem modelled within SENSUS include power generation, accumulation, consumption, and distribution.

1. **Power generation**: the power generated by solar panels is computed considering the cell characteristics, array configuration, and working mode. The position and inclination of the panel is influenced by the satellite translational and rotational state, as well as by the presence of solar array drive mechanisms. The presence of eclipse periods is also taken into account.

2. **Power consumption and distribution**: the power consumption in either active or idle modes is computed for all the most power-consuming components and distributed to the components considering their sample time and periods of usage.

3. **Power accumulation**: power storage is modeled with batteries, that can either supply energy when the generated power is not enough, or be recharged during periods of high power generation. The default battery charging behavior is composed by a first part in constant current charging, followed by constant voltage charging phase. The battery SOC to switch from one to the other can either be specified or kept at the default value (0.9).

2.6 Propulsion subsystem

The Propulsion Subsystem provides controlled thrust to adjust the satellite's orbit, perform station-keeping, or execute attitude maneuvers. The reaction control thrusters described in Section 2.3 can be used for both attitude and orbital maneuvers. Moreover, the simulator grants the possibility to include a non-steerable main engine placed in the center of one of the faces and with axis passing through the satellite center of gravity to limit attitude perturbations. The configuration parameters that need to be specified are:

- **Presence, type and position of main engine**: if the satellite includes a main engine, then its position in terms of satellite face must be specified. The simulation platform supports chemical of electric propulsion systems.

- **Propellant properties**: the propellant mass, specific impulse and propellant consumption rate are required by the simulation.

Whenever a maneuver is required, the propulsive system needs the specification of the burning time and required ΔV to reach the desired position. The maneuver can also be planned, and in this case, the specific time of the maneuver event must be added to the set of inputs. The only block included in this part of the model has the task to reproduce the propulsion system:

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1. **Propulsion system**: the propulsive system has been modeled behaviorally, and computes the thrust for the maneuver considering the propellant mass flow rate, required ΔV and burning time. The output thrust takes into account losses and limiting values. The same description applies to both chemical and electric propulsion systems, as at this stage, no in-depth modeling of the internal functioning of the system has been conducted.

2.7 TT&C and Communication channel

The Telemetry and Telecommand (TT&C) subsystem enables two-way communication between the satellite and the ground station. It sends telemetry data (status, health, and measurements of onboard systems) and receives telecommands to execute orbit maneuvers. This module requires the configuration of:

- **Ground station location**: the latitude, longitude and altitude coordinates of the all the ground stations that will be of interest in the simulation need to be configured at the beginning of the simulation.
- **Communication channel characteristics**: nominal signal frequency in uplink and downlink need to be specified. Moreover, all the characteristics related to the link budget are required in order to compute Earth-space propagation losses.
- **Antenna characteristics**: antenna beamwidth and limiting elevation are used to assess ground station visibility and access during the simulation.

Figure 4 displays a schematic architecture of the part of the simulator involving the flow of information from the ground station to the satellite and viceversa. Uplink communication starts from the ground station, reaches the satellite receiver antenna after being subjected to propagation losses, is checked and processed as a telecommand in the satellite TT&C module and is then handled by the satellite OBC. All the primary submodules composing the communication channel are clearly visible in the diagram. The downlink signal follows the opposite path, telemetry packets are prepared in the OBC module, and sent to the ground station through the communication channel.

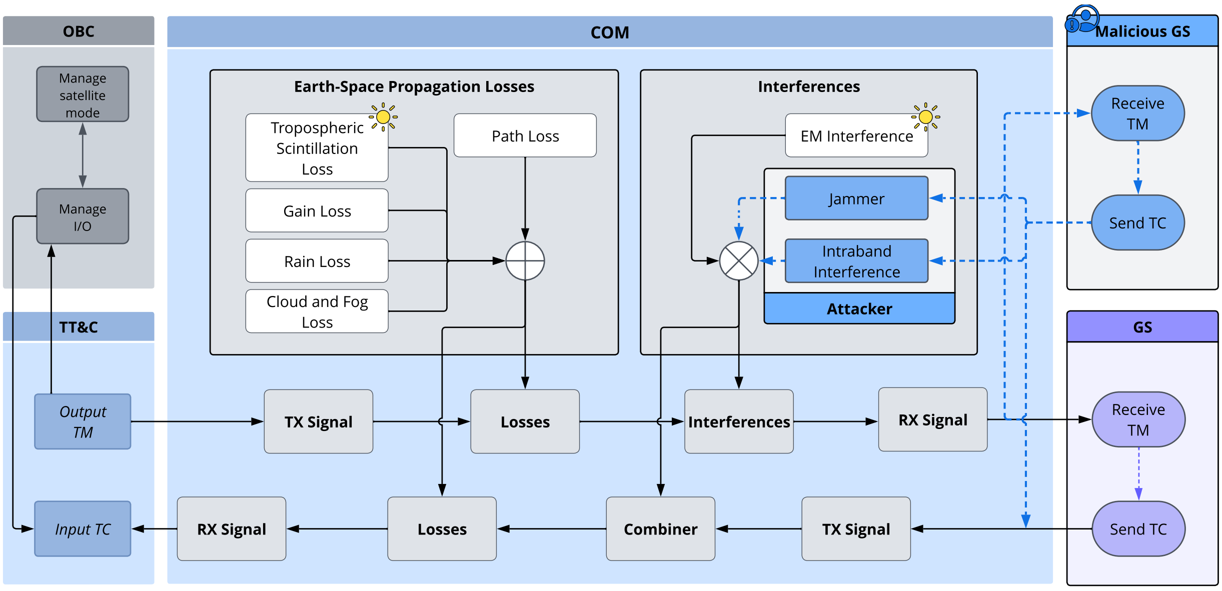

Figure 4: Architecture of TT&C, communication and ground station interaction

The following list of tasks is restricted to the most important ones:

1. **Ground station access and visibility**: a dedicated part of the simulator computes the satellite geographical coordinates, reproduces the orbital groundtrack and defines the ground station visibility and access time depending on the antenna characteristics.
2. **Telemetry and Telecommands**: the TT&C module represents the interface between the satellite and the communication channel. Output telemetry and input telecommand messages are processed within this block before being sent to ground or other satellite modules respectively.

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3. **Atmospheric losses**: the overall atmospheric attenuation is computed considering the combined effect of both the non-ionized atmosphere (gas, cloud, rain and scintillation) and the ionosphere. These contributions are related to the probability that a given attenuation level is exceeded.
4. **Interference**: signals in both dowlink and uplink can be subjected to interference. The two sources of EM interference captured by the simulator are space weather events, mainly solar flares, or cybersecurity attacks.

2.8 Satellite OBC

The Onboard Computer (OBC) is the central processing unit of the satellite, responsible for executing commands, managing subsystem operations, processing sensor data, and running control algorithms. It handles real-time decision-making, fault detection, and communication with the ground station and other subsystems. The OBC within SENSUS is represented by a state machine modeled in Simulink Stateflow, and manages the satellite operative modes. The satellite can operate in different modes, depending on the mission objective, communication type, and system configuration. These modes define how the submodules behave and how satellite interacts with ground station. Components and subsystems are active or inactive depending on the satellite mode. Table 1 presents a summary of the functionalities of each subsystem in different operational modes.

Mode	Nominal Mode	Safe Mode	Science / Payload Mode	Communication Mode	Eclipse Mode
AOCS	Maintains precise attitude (e.g., Earth-pointing)	Switches to Sun-pointing for power generation	Maintains precise attitude	Aligns antenna for optimal link	Maintains attitude
EPS	Nominal functionalities	Reduces consumption; powers only critical systems	Solar panels working mode can be MPPT; Priority to power payload	Priority to power communication hardware	Operates on battery, conserves power
THM	Nominal temperature monitoring; Thermal active control	Prevents critical components from overheating / freezing	Regulates temperature for sensitive instruments	Nominal temperature monitoring; Thermal active control	Nominal temperature monitoring; Thermal active control
COM	Handles telemetry and telecommands	Sends minimal telemetry	High-rate data downlink for payload	Enables continuous two-way link with ground	Sends minimal telemetry, if necessary
PROP	Can performs maneuvers	Off	Can perform maneuvers	Off	Can performs maneuvers

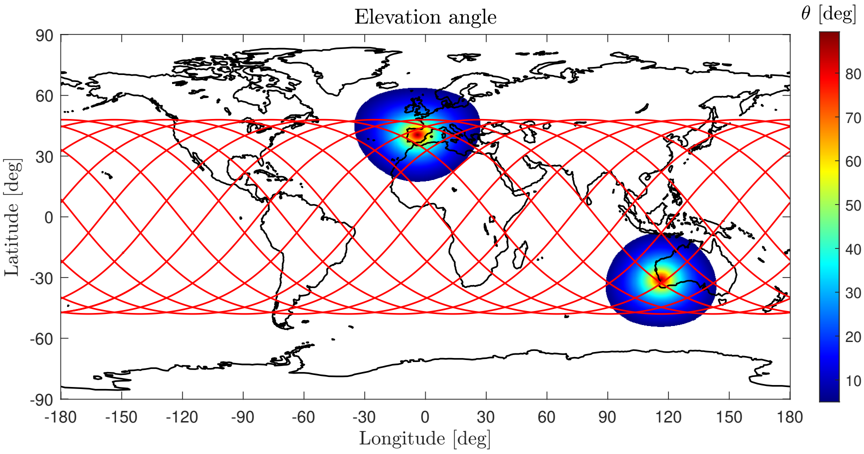
Table 1: Behavior of satellite subsystems across operational modes

2.9 Overview of outputs

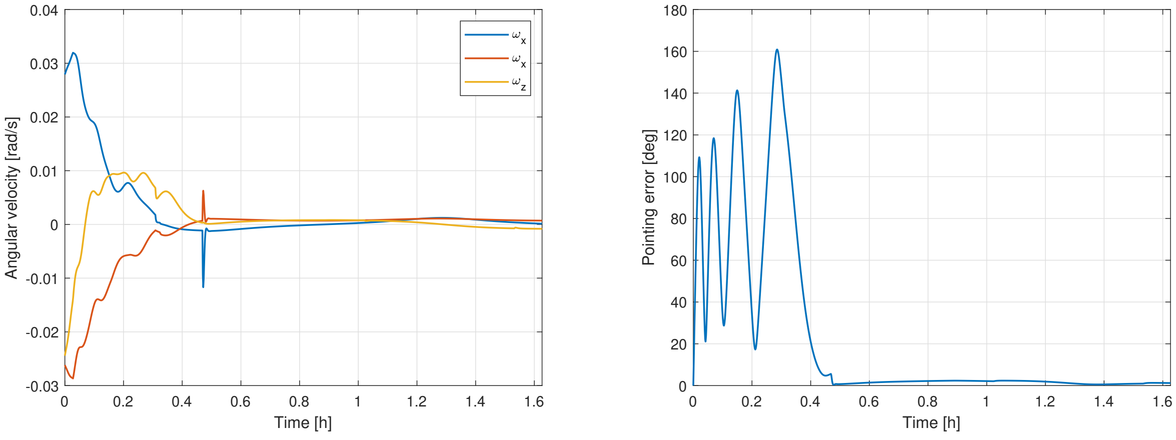
A fundamental part of the development of the simulator is the validation of the modeled subsystems. Validation has been carried out through different means, the most relevant being the comparison with other existing tools, reproduction of books and review papers results, and comparison with Matlab built-in functions.

All the variables computed within the simulation can be accessed and promoted to simulation outputs. Figure 5 shows a subset of the possible states that can be visualized during the simulation. The mission scenario included a LEO orbit, with satellite AOCS performing detumbling with magnetorquers, followed by slew maneuver and pointing to the reference attitude using reaction wheels. The simulation lasts for one orbit, and the satellite experience an eclipse phase after the first hour. Figure 5(a) presents a 3D view of the satellite along its orbit around Earth. Figure 5(b) presents a visualization of visibility and access areas among the satellite and two different ground stations, with the satellite groundtrack over multiple orbits plotted for reference. Figure 5(c) shows the three component of the angular velocity ω of the satellite: one can notice a first part dominated by velocity reduction during the detumbling phase, a spike corresponding to the satellite reorienting and then a stable behavior. Lastly, Figure 5(d) depicts the pointing error of the satellite with respect to desired attitude, from which the three attitude phases are clearly distinguishable.

(a) 3D view of the satellite along its orbit



(b) Areas of visibility and access to two possible ground stations



(c) Angular velocity of the satellite

(d) Pointing error with respect to desired attitude

Figure 5: Examples of plots resulting from SENSUS

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3. Space Weather Impact on Space Systems

Space weather refers to variable conditions on the Sun, in space, and in Earth's magnetic field and upper atmosphere that can affect both space-based and ground-based systems. It includes phenomena such as solar flares, geomagnetic storms, and interactions with space debris or micrometeoroids. Its impacts are broad: satellites may suffer operational issues, orbital drift, and communication disruptions; on Earth, space weather can disturb radio signals, GPS, power grids, oil and gas extraction, and aviation. A notable example is the 2003 Halloween storms, during which several satellites malfunctioned, one was lost, polar flights were rerouted, a blackout occurred in Sweden, and infrastructure such as oil rigs and power transformers experienced failures.

3.1 Space weather threats and failure mechanisms

Space weather actors are numerous, and all concur in causing possible threats and failures to satellite systems. Figure 6 tries to capture the most important connections among space weather sources, emission of particles and/or electromagnetic (EM) radiation, and the final macroscopic effect that a satellite can experience.

The Sun is the major contribution to space weather, emitting solar flares (SF), coronal mass ejections (CME) and solar wind. **Solar flares** are sudden, intense bursts of electromagnetic radiation from the Sun, caused by magnetic field reconfigurations in the solar corona. They emit energy across the electromagnetic spectrum, from radio waves to X-rays, and the radiation reaches Earth in about 8 minutes. SFs are often accompanied by high-speed particles, including protons and electrons, which can disrupt satellite operations, pose radiation risks to astronauts, affect aircraft electronics, and increase radiation exposure at flight altitudes. The flares also disturb Earth's ionosphere, increasing its conductivity and generating currents that cause rapid magnetic field fluctuations.[8][5][1] **Coronal Mass Ejections** (CMEs) are large bursts of plasma ejected from the Sun, often associated with solar flares. Traveling up to 3000 km/s, they take 3–5 days to reach Earth due to solar wind slowing them down. When a CME's magnetic field interacts with Earth's, alignment determines the effect: parallel fields offer protection, while opposing fields cause magnetic reconnection, allowing solar particles to penetrate Earth's magnetosphere. This can produce auroras but also disrupt infrastructure. Notable events include the 1989 Quebec blackout and the 2003 "Halloween storms," which affected satellite operations.[8]

Galactic cosmic rays (GCRs) consist of high-energy particles from supernova shock waves and exhibit an inverse relationship with solar activity. During weak solar cycles, GCR flux increases, presenting radiation exposure risks to astronauts and aircrew.[8]

The Van Allen **radiation belts** are two doughnut-shaped regions of highly energetic, charged electrons and protons trapped by Earth's magnetic field. The inner belt, located about 1000 to 12000 kilometers above Earth, consists mainly

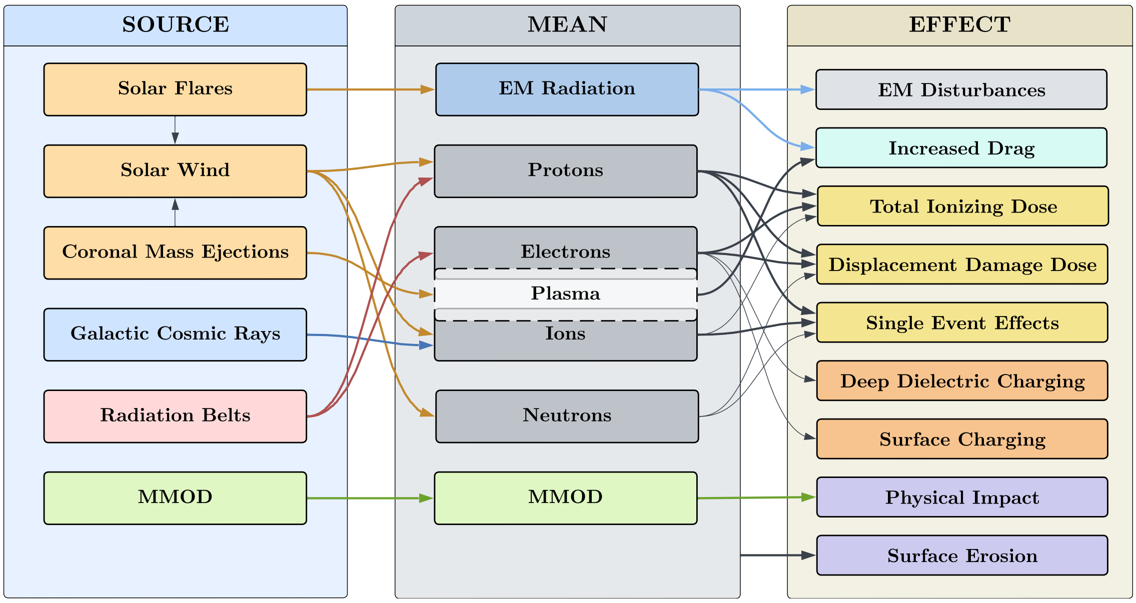

Figure 6: Overview of space weather effect on satellites

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of protons from cosmic ray interactions with the atmosphere. The outer belt, extending from roughly 13000 to 60000 kilometers, is dominated by electrons energized by interactions with solar wind and geomagnetic storms. These belts pose significant hazards to satellites and astronauts due to the high radiation levels.

Micrometeoroids are tiny particles of natural origin, primarily fragments of comets and asteroids, that travel through space at extremely high velocities. **Orbital debris**, on the other hand, are human-made and include defunct satellites, spent rocket stages, fragments from satellite collisions or explosions, and other remnants of space missions. Due to their high relative speed, which often exceeds 10 km/s, they can cause severe damage to space systems.

All the listed sources, except for the particular case of MMOD, emit EM radiation, energetic particles, or both. The interaction of photon and charged particles with any material emits electrons and creates electron-hole-pairs along their track, causing ionization of the matter. **Total Ionizing Dose** (TID) is the overall absorbed dose generated on a target material from the energy deposition of ionizing radiation. Total ionizing dose results in cumulative parametric degradation that can lead to functional failure.[7]

When a particle impacts on a target material, the majority of its incident kinetic energy is lost to ionization, contributing to TID and generating single-event effects. However, a small portion of energy is lost in non-ionizing processes, which cause atoms to be removed from their lattice sites, creating permanent electrically active defects in semiconductor materials. **Displacement damage dose** (DDD) is the cumulative degradation resulting from this non-ionizing energy loss, and can lead to functional failure of the component. Optoelectronic components like photodetectors and CCDs show high sensitivity to displacement damage. Additionally, solar cells are vulnerable to both ionizing dose and displacement damage.

Single-event effects (SEEs) can be caused by energetic particles of different natures and sources; the three major ones are particles expelled during solar events, high-energy protons trapped within Earth's radiation belts, and galactic cosmic rays.[2] Space weather events such as solar flares and CMEs generate a flux of protons and heavier particles, with proton energies surpassing 100 MeV. Major solar proton events can induce single-event effects on spacecrafts and contribute to the deterioration of solar arrays. Galactic cosmic rays are highly efficient in inducing single-event upsets, even though their flux is relatively weak. Due to their energy, solar protons and galactic cosmic rays can induce single-event effects in moderately radiation-hardened electronics. Trapped high-energy protons in the inner radiation belts can reach levels exceeding 10^8 protons/(m^2-s-sr) for energies above 50 MeV. Particles at this energy level can also impact components with low linear energy transfer thresholds. The South Atlantic Anomaly poses a specific risk

Table 2: Selected SW attacks

Anomaly	Subsystems/Modules	Macroscopic effect
Data corruption	Subsystem level/ TT&C level - All electronics components	Can be categorized in 3 levels: 1. Irrelevant (corruption of last significant bit makes unnoticeable/ small changes in value) 2. Plausible (corruption of bit in the middle of the word makes noticeable/ quite big changes in value 3. Unplausible (corruption of first significant bit of the word changes value to out-of-range value)
Noise on optical instruments	AOCS	Random pixels illuminated or not illuminated change instantaneous ST performance 1. Error in the measure 2. No measure
System shutdowns	All electronics components	System stops working for as long as recovery time
Electronic component damage	All electronics components	System stops working permanently
Increased atmospheric drag	ENV, AOCS	Larger errors in knowledge of atmospheric density, higher drag coefficient
Signal degradation and loss	TT&C, COM	No command received
Radio blackout	TT&C, COM	No command received

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due to geomagnetic field asymmetries that draw radiation belts nearer to Earth in this area.

Table 2 presents a summarized overview of the anomalies and failure mechanisms considered in the context of the presented simulation platform, specifying the subsystem or submodule involved, as well as the macroscopic effect caused on the satellite. As widely explained in literature, satellites experience the most of the anomalies within their electronic components and on the communication channel. However, when considering space weather, particular attention needs to be given to optical instruments. Optical sensors onboard satellites, such as star trackers and imaging devices, are particularly vulnerable to space radiation due to their sensitivity to charge deposition. Radiation effects can be transient, semi-permanent, or permanent, and can significantly degrade sensor performance. Transient effects, such as SEEs, are caused by ionizing particles like protons or heavy ions, which generate false signals (bright pixels) on detectors. These are especially common in orbits that cross the Van Allen belts or the South Atlantic Anomaly. In star trackers, which use CCD or APS detectors to match observed stars with onboard catalogs, SEEs can mislead star recognition algorithms and compromise attitude determination, particularly during periods of intense solar activity. Displacement damage from protons can lead to semi-permanent or permanent degradation of detector performance. This includes the appearance of *hot pixels* (persistent dark current spikes) and dark current instability, where the current fluctuates unpredictably over time. Additionally, long-term effects like Total Ionizing Dose and Displacement Damage Dose gradually increase the average dark current and reduce the uniformity of pixel response, lowering the signal-to-noise ratio.

4. Cybersecurity Impact on Space Systems

Space systems are essential to modern life, supporting climate monitoring, transportation, telecommunications, and national defense. However, as space assets become more advanced and interconnected, they are increasingly vulnerable to cyber threats. Satellites today operate like airborne computers, facing risks similar to those of terrestrial systems, including malware, hacking, and data breaches. Their reliance on ground stations and global networks further expands the attack surface. The lack of standardized cybersecurity frameworks in the space sector amplifies these risks. Cyberattacks targeting satellites or their supporting infrastructure can have serious consequences for public safety, national security, and the global economy. As space becomes a contested domain, prioritizing cybersecurity throughout the lifecycle of space systems is critical. Given the high cost of building full-scale replicas, simulation emerges as a practical approach. Software models of satellites can replicate system behavior and support early detection of vulnerabilities. Integrated into cyber ranges, these simulations allow for testing the impact of cyberattacks in realistic environments without endangering real assets. Traditional cyber ranges focus on IT systems and often neglect the full complexity of space infrastructure. To close this gap, there is a pressing need for innovative simulation frameworks that combine satellite models, the surrounding physical environment, and ground segments. Such tools enable comprehensive cybersecurity testing and serve as valuable resources for training mission operators in defending space systems.

4.1 Space cyber-security threats and failures mechanisms

Identifying vulnerabilities in satellite systems is critical to protecting space infrastructure from cyber threats. As satellites increasingly depend on complex software and maintain constant interaction with ground and orbital networks, they present multiple entry points for potential attacks. Vulnerabilities in onboard software, communication links, or access control can be exploited to disrupt operations, compromise data, or even seize control of a satellite. This highlights the need for secure-by-design architectures and systematic vulnerability assessments.

Demonstrative exercises are essential for uncovering and addressing these weaknesses. During the third edition of CYSAT, a European event focused on space cybersecurity, a controlled cyberattack was conducted on ESA's OPS-SAT nanosatellite. Developed as an experimental platform, OPS-SAT was targeted in an offensive cybersecurity challenge by a team from Thales, supported by the Information Technology Security Evaluation Facility. The team successfully exploited standard access rights to enter the application environment and manipulate critical subsystems such as sensor control, geolocation, attitude control, and camera functions. They also injected malicious code to alter downlinked data, for example by masking specific geographic areas. This exercise demonstrated the real risk of undetected intrusions and the urgent need for cyber resilience in satellite missions.

In a similar effort, the Hack-A-Sat competition, organized by the U.S. Air Force and Space Force, brings together cybersecurity professionals to identify and exploit vulnerabilities in satellite systems through capture-the-flag challenges. In recent editions, participants were given access to a dedicated CubeSat in orbit, allowing them to test attack and defense scenarios in a realistic space environment. These initiatives not only expose critical flaws but also promote collaboration between cybersecurity experts and space engineers, helping to improve the overall security of future satellite missions.

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To support these efforts, specialized frameworks have been developed to systematically identify and categorize potential cyber threats to space systems. The Aerospace Corporation's Space Attack Research and Tactic Analysis (SPARTA)[10] framework offers a comprehensive matrix that maps out tactics, techniques, and procedures (TTPs) that adversaries might employ to compromise spacecraft. SPARTA serves as a valuable resource for spacecraft developers, owners, and operators to understand potential attack vectors and implement appropriate countermeasures. Similarly, ESA's SPACE-SHIELD (Space Attacks and Countermeasures Engineering Shield)[3] provides a knowledge base tailored to space systems, focusing on adversary TTPs relevant to the space segment and communication links. These frameworks facilitate a standardized approach to threat modeling and enhance the cybersecurity posture of space missions. Table 3 describes the cyber attacks that were selected to be implemented within SENSUS. They mainly include attacks on the communication channel, but also the possibility of manipulating data and tampering sensor readings.

Table 3: Selected cyber attacks

Target	Attack scenario	Description	Effect on satellite
GS	Jamming	Disallows the ground equipment to communicate with the satellite, both in downlink and uplink	No message sent / No command received
SAT	Channel Flooding	Satellite communication is disrupted by transmitting malicious, intercepted, or superfluous data on the satellite's channel, causing an excessive data load that overwhelms the satellite's processing capabilities	Impaired processing of external commands / No command received
SAT, GS	TC&TM Data Leak and Data Forgery	Insufficient or absent encryption in TC and/or absence of authentication allows attackers to forge telecommands and/or leak telemetry data.	Receiving wrong commands
SAT, GS	Person in The Middle	An attacker alters the original telecommands to transmit erroneous directives to the satellite.	Receiving wrong commands
SAT	Destructive Data Forgery	Deliberate manipulation of satellite sensor readings to induce destructive actions, such as manoeuvres, overheating, or excessive power consumption.	Modification of sensor readings to induce destructive actions
SAT	Degradation Data Forgery	Deliberate manipulation of sensor readings triggers the misuse of FDIR systems, causing the forced activation of satellite's safe mode.	Modification of sensor readings to trigger safe mode

5. Conclusions

SENSUS is a comprehensive simulation framework for modeling satellite subsystems and their interactions with the space environment. Its strength lies in the integration of multi-physical models, including AOCS, EPS, thermal, propulsion, OBC, and TT&C, within a unified and modular platform built using MATLAB, Simulink, and Simscape. The simulator enables realistic reproduction of both nominal and anomalous behavior by accounting for external factors related to space weather and cybersecurity threats. With its inherent capability of modeling space systems, SENSUS provides a powerful tool for satellite simulations, and contributes in bridging the existing gap between satellite operation community, cyber-security efforts and space weather research.

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