The Pennsylvania State University

The Graduate School

DYNAMIC MODELING OF A POWER PROFILE FOR SMALLSAT COGNITIVE AGENTS

A Thesis in

Electrical Engineering

by

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of the Requirements
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ABSTRACT

This thesis developed a methodology for simulating the power profile of a small satellite cluster in order to verify mission requirements during the early stages of mission development. Power System simulation models have become an indispensable tool for the research, design, and development of more adaptable satellite management systems. Transforming models into an integrated, dynamic simulation allows for the creation of more complete power profiles that provide a simulated resource instance for the battery, solar panels, and additional electrical power system hardware components. Specifically, this study focuses on the simulation of electrical power profile behavior using real-time orbital parameters supported by the Satellite Orbit Analysis Program (SOAP) simulation and visualization software. The study utilized the SOAP environment to set up representative scenarios of the mission and to adequately characterize the power profile of a small satellite cluster in Low Earth Orbit.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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Chapter 1

INTRODUCTION

The preliminary design for the power subsystem of a small satellite includes identifying design requirements for its electrical power profile; selecting and sizing the power source for load requirements; selecting and sizing the energy source; and identifying power regulation and control. Predicting the dynamic power profile is important at an early stage of system development to verify mission requirements can be met. The Satellite Orbit Analysis Program (SOAP) software serves as an indispensable tool for the research, design, and development of satellite power management systems. Gaps in knowledge and system planning can be filled by apportioning the Satellite System into building blocks or modules for a reusable and scalable power system architecture [Lim, 2018]. SOAP enables the creation of subsystem modules used in dynamic power system simulation environments. Moreover, SOAP enables the characterization of power profiles that include orbital parameters, and 3D visualization of those orbits. This study focuses on the planning stages for a power management system by developing the electrical power profile within SOAP to support the Space Environment and Satellite Systems research at Penn State.

Space Environment and Satellite Systems

The primary purpose of the Space Environment and Satellite Systems research effort is to develop high-fidelity modeling systems that support mission requirements, test and evaluation, and vehicle health status reporting for a representative Low Earth Orbit (LEO) Small Satellite mission. The Satellite System typically is comprised of a ground station, satellite, and the environment in which it operates. The satellite is composed of payload(s) and several subsystems required for operation: Electrical Power System (EPS), Attitude Determination and Control System (ADCS), Communications (COM), Telemetry, Tracking, and Commanding (TT&C), and Thermal. At the ground station and on the satellite, there are several software components for planning, scheduling, and commanding.

As illustrated in Figure 1-1, the high-fidelity modeling environment requires real-time inter- and intra-satellite communications and seamless subsystem control decisions for the subsystems required for operation. To compensate for the complex challenges of the space environment, satellite systems are transitioning to automating mission operations and task planning with Artificial Intelligence (AI). The development of cognitive technologies is a recent thrust in the architecture of satellite systems. By applying AI and machine learning, satellite control systems can autonomously make real-time decisions [Sharma, 2012]. Implementing AI-based technology in space systems requires an understanding of the resource availability that powers and supports the communication between subsystem Cognitive Agents (CAs) and satellite subsystem components.

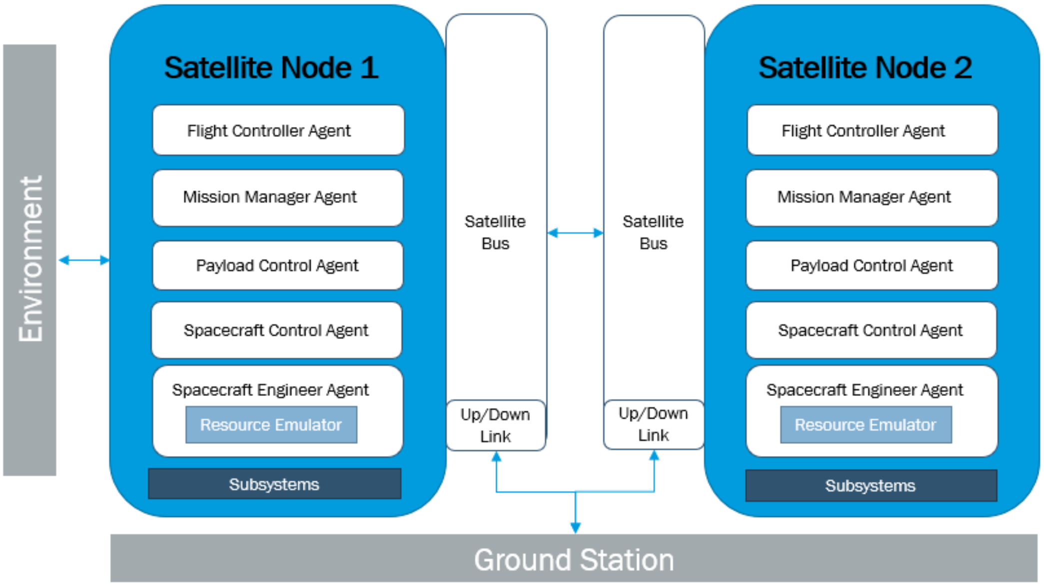

Figure 1-1 Satellite Modeling System Research Overview

The small satellite in this study conducts mission operations using a CA architecture. The CA architecture supports multiple CAs that contain cognitive, computational, and communication layers. These layers support decision-making, data interpretation, and message traffic facilitation between CAs. The Space Environment and Satellite Systems model apportions responsibilities to Flight Controller (FC) and Mission Management (MM) CAs, which are tasked with maintaining the operation of the satellite toward its mission goals. The CA planning is accomplished by considering power and storage restrictions among the implemented satellite cluster. To define operational constraints and monitor resource availability, a SOAP simulation analysis was introduced to improve the learning of the CAs for mission assurance.

Figure 1-2 provides an overview of the components of a satellite system. This work focused on power generation governed by a common solar power architecture. The SOAP simulation addresses the modeling of the power available from the solar panels, which is used as an input for the power profile that is required by the Satellite System Electrical Power System and Battery.

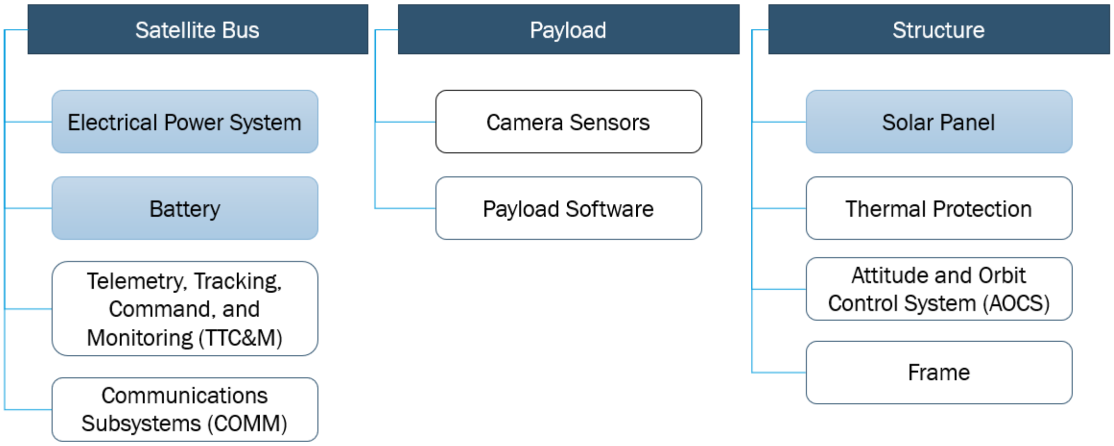

Figure 1-2 Overview of Satellite System

Research Contributions

This study entails the research, development, and verification of a conceptual and analytical model of the power profile for the SOAP Small Satellite Cluster (consisting of four satellites labeled Sat1–Sat4), shown in Figure 1-3. The scenario mission provides *in situ* and orbit-average power calculations to understand the available energy resource profile for reliable satellite operations. The orbital parameters are targeted to represent a polar low-Earth-orbit (LEO) between altitudes of 700 and 800 kilometers and inclinations between 60 and 90 degrees.

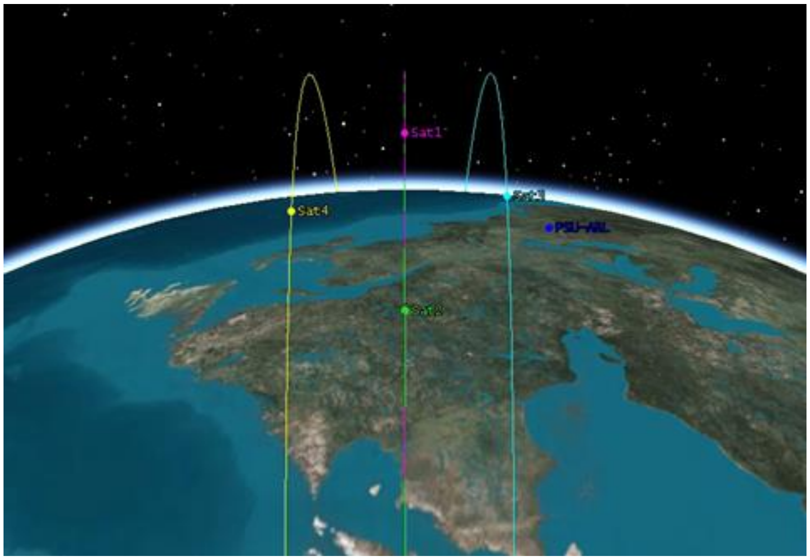

Figure 1-3: SOAP Scenario Satellite Cluster.

Theoretical and mathematical development for estimating the small satellite’s available energy is discussed in detail in the following chapters, as well as the development of the SOAP models. Additionally, to verify that the model behaves as anticipated, the SOAP models is performed by developing a simulation in SOAP of a small satellite with body-mounted solar panels similar to the Solar Panel Tool in Systems Tool Kit (STK).

Overview of Thesis

This thesis provides contributions to the simulation of the Satellite Environment and Satellite Systems power management system by providing the theory behind the power analysis of a small satellite (Chapter 2), as well as the development of a dynamic simulation in SOAP to calculate the solar incidence of the satellite solar sections.

Results are provided for the solar irradiance for each small satellite solar panel. Solution of the power profiles over time obtained from the small satellite with sensor slewing systems are discussed and analyzed (Chapter 3). Results of the power output and efficiency of the leveraged SOAP functionalities are given for the solar power generator module’s capability to estimate the energy budget (Chapter 4). Chapter 5 concludes the thesis and provides directions for future work.

Chapter 2

Modeling and Simulation in SOAP

To support system integration, testing, and evaluation, the Satellite Environment and Satellite Systems modeling requires tools to capture the resource usage for each component, which enables an understanding the power requirements of the satellite bus and ensures payload health. This chapter overviews the visualization study of the electrical power system that was modeled and simulated within the existing functionalities of the Satellite Orbit Analysis Program (SOAP). The SOAP tool was used to add weight to the analysis and discussion of the Electrical Power System emulator that interfaces to the Flight Controller and Mission Management CAs.

Introduction to SOAP

The SOAP tool was developed and is maintained by The Aerospace Corporation. It is restricted to U.S. entities, i.e., government agencies and personnel and U.S. corporations with a current government contract involving space systems. The overall architecture of SOAP includes the OpenGL Application Programmers Interface (API) and Qt development framework under the Limited GNU Public License (LGPL). SOAP is an interactive software that employs 3D graphics animation to display the relative motion of spacecraft systems. SOAP provides analysis, visualization, and simulation capabilities that can answer a variety of questions that commonly arise in space system modeling. A description of the building blocks of the SOAP simulation are presented in the sections below. The building blocks, referred to as objects in SOAP, include basic object types such as Platforms and Coordinate Systems for complex objects such as Sensors and 3D Models.

The Earth

The Earth is an object within SOAP, shown in Figure 2-1, and how it is modeled affects every computational result. SOAP employs WGS84 physical constants to model the Earth, which are presented in Table 2.1 [SOAP, 2020].

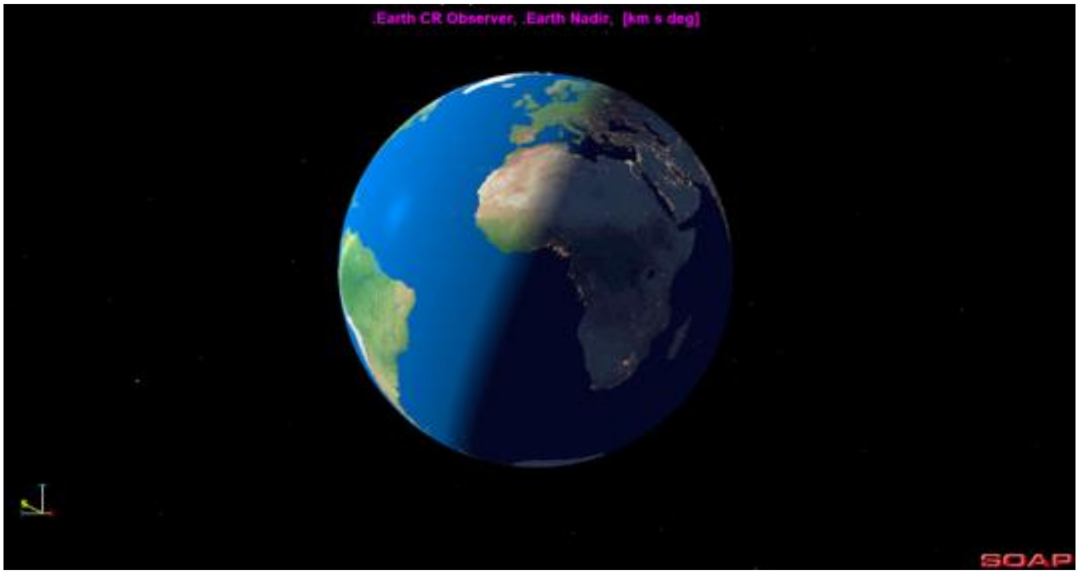

Figure 2-1 Earth View in SOAP

Table 2.1 Earth Constants

Earth Parameter	**Value**	**Units**
Mean equator radius	6.378137000e+3	km
Flattening coefficient	3.35281066474748e−3	unitless
Gravitational parameter	3.986004418e+5	km^3/s^2
J2 zonal harmonic	1.08262668355315e−3	unitless

Rotational rate	4.17807421629331e−3	degrees/s

The rotational rate of the Earth varies slightly, but SOAP does not model this variation. Assuming a constant rotational rate, the Earth makes a complete rotation about its axis in one sidereal day. SOAP allows users to override these constants, and rotational rate can be overridden either directly or through a Spacecraft Planet, Instrument, C-Matrix, and Events (SPICE) Frame Kernel with the permission of the Navigation Ancillary Information Facility (NAIF). SPICE is a system developed by the NAIF at the Jet Propulsion Laboratory (JPL) for organizing and accessing space geometry and event data to propagate the spacecraft and planetary ephemeris, orientating planetary bodies. The rotational rate and constants for the Earth model were not overridden for this simulation study. The location of the Earth Platform is considered the origin of the Earth Centered Inertial *(ECI) Coordinate System* and, thus, it is not propagated. Precession and nutation are not considered for the orientation of the Earth. Measurement of time is based on the position and orientation of the Earth relative to the Sun.

Platform Definition

Platforms represent point entities having position and velocity (satellites, ground stations, and planet centers). In SOAP, the platforms represent moving points in space. The rules that govern how a platform moves are embodied in internal algorithms called Propagators. Platforms are categorized into several types, based on which propagation method is employed. Platform initial conditions define a known state represented by position and velocity at a given time. The format of the initial conditions depends on the Platform type, as selected from the Objects panel. The behavior of a platform as a function of time depends on both the initial conditions and the Platform type. Once a platform is defined, it may have SOAP objects such as Sensors, Analysis, and Views attached to it. The animation computational speed may be adversely affected if too many platforms are defined.

Predefined Platforms are used to represent planet centers, barycenters, natural satellites (moons), asteroids, comets, and the Sun. Spacecraft orbits are propagated using Kepler, NORAD, and Low-Trust Platforms in SOAP. Predefined Platforms are those automatically generated by SOAP, including the Earth, Sun, and Moon. SOAP Predefined Platforms all share the property that the user cannot directly change their prescribed motion. The Earth, Sun, and Moon are internally generated in SOAP, but also have the SPICE IDs.

SOAP has internal models of the Earth, Moon, and Sun platforms. The Earth is always assumed to lie at the origin of the SOAP universe, and so its motion is not modeled as such. However, the motion of the Earth can be deduced by examining the motion of other massive bodies, such as the Moon and Sun. The SOAP Earth, Sun, and Moon are represented by Predefined Platforms and their initial conditions are defined internally and the user has no control over them. Only single instances of these Platforms can exist, and they cannot be deleted. The Earth, Moon, and Sun platform positions are at the geometric center of each respective object.

NORAD Platform

The North American Aerospace Defense Command (NORAD) provides inventory and generates the mean orbital elements of all orbiting space objects that they track (generally those larger than ~10 cm in diameter). The NORAD element sets are mean values and must be used with one of the models employed by the propagators described in Hoots & Roehrich [1980] to retain maximum prediction accuracy. The most common of them is the NASA/NORAD Two-Line Elements (TLE) format. Orbital positions can be calculated from TLEs through Simplified General Perturbation (SGP) SGP4/SDP4/SGP8/SDP8 algorithms. The osculating orbital position and velocity of the LEO satellites can be propagated from the NORAD TLE using the general perturbation formula such as Simplified General Perturbation 4 (SGP4) model [Hoots & Roehrich, 1980].

In this work, the SOAP NORAD Platform is used to model the motion of the scenario LEO Satellites in circular or elliptical orbits about the Earth. SOAP uses the Vallado version for the NORAD SGP4, SDP4, and SGP propagators to update the satellite position and velocity [Vallado, 2006]. The initial conditions provided in Tables 2.2–2.6 were set as inputs for the SGP family of propagators developed by agencies of the Air Force Space Command (AFSPC). The NORAD TLE version used for this scenario is SGP4 Vallado Version 3.0 developed by Ken Cranford in 1970 [Lane, 1979] for near-Earth satellites. Due to restrictions on the distribution of NORAD TLEs, the original source of TLE data is not provided in SOAP.

Table 2.2 Initial Conditions of NORAD Platform

Name	**Units**	**Description**
NORAD Sat Number	integer-valued	for identification only
Epoch	days	day and fraction of day
Xndt20	revs/day^2	1st derivative of mean motion / 2
Xndt60	revs/day^3	2nd derivative of mean motion / 6
Ballistic coefficient	(Earth radii)$^{-1}$	BSTAR atmospheric drag term
Ephemeris type	integer-valued	0=SGP4/SDP4, 1=SGP, 2=SGP4, 3=SDP4
Inclination	degrees	elevation above equatorial plane
Right ascension	degrees	right ascension of the ascending node
Eccentricity	unitless	$0 <= e < 1$
Mean Motion	revs/day	number of orbit periods per day
Revolution Number	integer-valued	number of periods since launch

Table 2.3 Platform Sat1 00867 NORAD Definition

Name	**Value**	**Units**
NORAD Sat Number	00867	unitless
Year	20	YY < 50 means 20YY
Epoch	342.59692852	days
Xndt20	1.103e-05	revs/day^2
Xndt60	0	revs/day^3
B-star	3.3518e-05	0:1
Eph Type	0	unitless
El Num	999	unitless
Inclination	89	deg
RA Node	252.7036	deg
Eccentricity	0.0003481	0:1
Arg Perigee	299.7327	deg
Mean Anomaly	312.3331	deg
Mean Motion	14.57922869	revs/day
Rev Num	177	unitless

Table 2.4 Platform Sat2 00865 NORAD Definition

Name	**Value**	**Units**
NORAD Sat Number	00865	unitless
Year	20	YY < 50 means 20YY
Epoch	342.59692852	days

Xndt20	1.103e-05	revs/day^2
Xndt60	0	revs/day^3
B-star	3.3518e-05	0:1
Eph Type	0	unitless
El Num	999	unitless
Inclination	89	deg
RA Node	252.7036	deg
Eccentricity	0.0003481	0:1
Arg Perigee	299.7327	deg
Mean Anomaly	288.331	deg
Mean Motion	14.57922869	revs/day
Rev Num	177	unitless

Table 2.5 Platform Sat3 00836 NORAD Definition

Name	**Value**	**Units**
NORAD Sat Number	00836	unitless
Year	20	YY < 50 means 20YY
Epoch	342.59692852	days
Xndt20	1.103e-05	revs/day^2
Xndt60	0	revs/day^3
B-star	3.3518e-05	0:1
Eph Type	0	unitless
El Num	999	unitless
Inclination	89	deg
RA Node	243.7036	deg
Eccentricity	0.0003481	0:1
Arg Perigee	299.7327	deg
Mean Anomaly	300.331	deg
Mean Motion	14.57922869	revs/day
Rev Num	177	unitless

Table 2.6 Platform Sat4 00896 NORAD Definition

Name	**Value**	**Units**
NORAD Sat Number	00896	unitless
Year	20	YY < 50 means 20YY
Epoch	342.59692852	days
Xndt20	1.103e-05	revs/day^2
Xndt60	0	revs/day^3
B-star	3.3518e-05	0:1

Eph Type	0	unitless
El Num	999	unitless
Inclination	89	deg
RA Node	261.7036	deg
Eccentricity	0.0003481	0:1
Arg Perigee	299.7327	deg
Mean Anomaly	300.331	deg
Mean Motion	14.57922869	revs/day
Rev Num	177	unitless

Platform Relative Platforms

Platform Relative Platforms are defined relative to other preexisting platforms. The *Platform Relative Platform* Coordinate System (CS) frame is an instance of a SOAP CS, a separately defined SOAP object type.

Table 2.7 Platform Solar Panel Relative Definition

Name	**Value**
Reference Platform	[Sat1, Sat2, Sat3, Sat4]
Input Frame	Spherical
Magnitude	0 deg
Theta +X →Y	0 deg
Phi +X →Y	0 deg
3D Model	Model [+X, +Y, +Z, −X, −Y, −Z]
Host Sensors	SunSensor [+X, +Y, +Z, −X, −Y, −Z]

In this study, the Solar Panel [+X, +Y, +Z, −X, −Y, −Z] sections were defined as Platform Relative to the Reference Platforms [Sat1, Sat2, Sat3, and Sat4]. The SOAP Platforms define the origin of the frame, and the CS defines the orientation of the Reference Platform frames.

As shown in Figure 2-2, the Solar Panel’s coordinate system was designed independently from the Reference Platform’s slewing coordinate system. In Figure 2-2, Satellite 1’s *Slewing Coordinate System* is located at the center of the structure body, where the Sat1 label is located. The *Solar Panel theta, phi Coordinate Systems* were placed on each face of the satellite for faces [+X, +Y, +Z, −X, −Y, −Z -X, -Y, -Z].

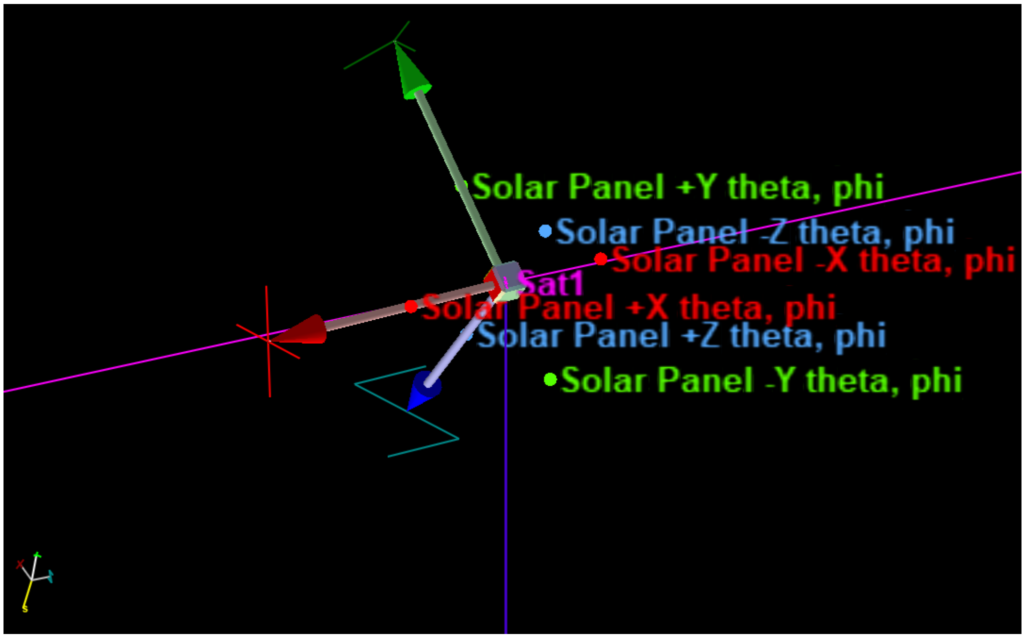

Figure 2-2 Slewing CS and Solar Panel CS on Satellite 1 3D Model

Table 2.8 Platform Solar Panel theta, phi Relative Definition

Name	**Value**
Coordinate System	Axis Solar Panel [+X, +Y, +Z, −X, −Y, −Z]
Reference Platform	Solar Panel [+X, +Y, +Z, −X, −Y, −Z]
Input Frame	Cartesian
X	0 m
Y	0 m
Z	1 m
3D Model	Model [+X, +Y, +Z, −X, −Y, −Z]
Host Sensors	SunSensor [+X, +Y, +Z, −X, −Y, −Z]

As shown in Table 2.8, a *Solar Panel theta, phi Platform Relative* was defined for all faces of the Reference Platforms [Sat1, Sat2, Sat3, and Sat4]. The Coordinate System frame controls how the axes of the 3D frame are aligned with respect to the SOAP coordinate frames. To support the visualization of the geometry, the 3D models had to be designed for each face and attached to the *Solar Panel Relative* and *Solar Panel theta, phi Relative* platform definitions comprised of their independent coordinate systems, defined as the *Axis Solar Panel* [+X, +Y, +Z, −X, −Y, −Z] discussed in the Coordinate System section. The *Solar Panel theta, phi Relative* platform definition Cartesian Z Input Frame is defined as 1 meter to shift the origin frame axes to an external point of the 3D satellite body structure in a +Z direction, similar to a representation of where the solar section normal plane would be placed theoretically for each side. If the Z Input Frame is kept at 0 meters, the solar section model performs the solar incidence calculations at the origin frame of the Reference Platform due to the provided 3D Models not accounting for internal or external body structures, the challenges are further discussed in the Physical Model section.

Platform Physical Model

The satellite models implemented leveraged the available SOAP Surface Based Model (SBM) files to represent the body structure of the satellite and the solar panels to support the visualization study, shown in Figure 2-3. SOAP SBM files are constructed in Computer Aided Design (CAD) programs and converted to the SBM format using OBJSBM or SOAP DXF-to-SBM utilities. The satellites implemented are not physical representations of the Satellite Environment and Satellite Systems' mission and are only used for preliminary modeling. The physical representation and geometry of the structures can be updated for the next iteration to improve modeling accuracy and representation. The theoretical scenario designed includes four satellites (Satellites 1-4) in a cluster in LEO.

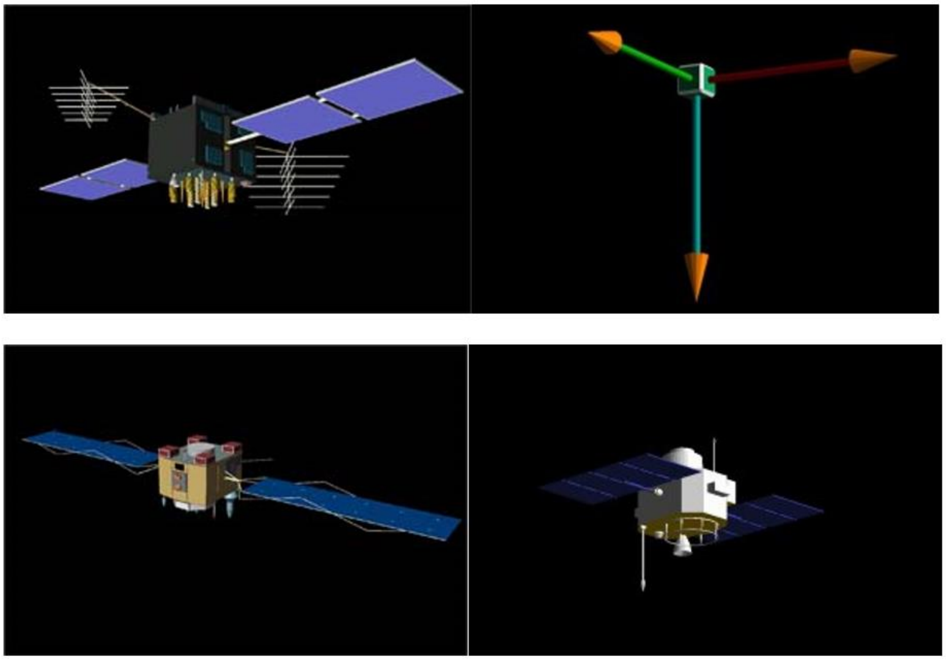

Figure 2-3 SOAP SBM 3D Models

The satellite system can be divided into three sections: bus, payload, and structure. The structure typically includes the frame, solar panels, attitude control, and thermal protection. As shown in Figure 2-4, Satellite 1-4 structures were designed using the SOAP 3D Model ID 'misc_triad.sbm' for the satellite body frame from the SOAP 3D Models panel and attached to the Reference Platforms [Sat1, Sat2, Sat3, and Sat4]. The

Satellite 1, labeled as *Sat1*, SBM 3D model and wire frame are two different views that can be displayed in SOAP when running the simulation, shown in Figure 2-4 and Figure 2-5.

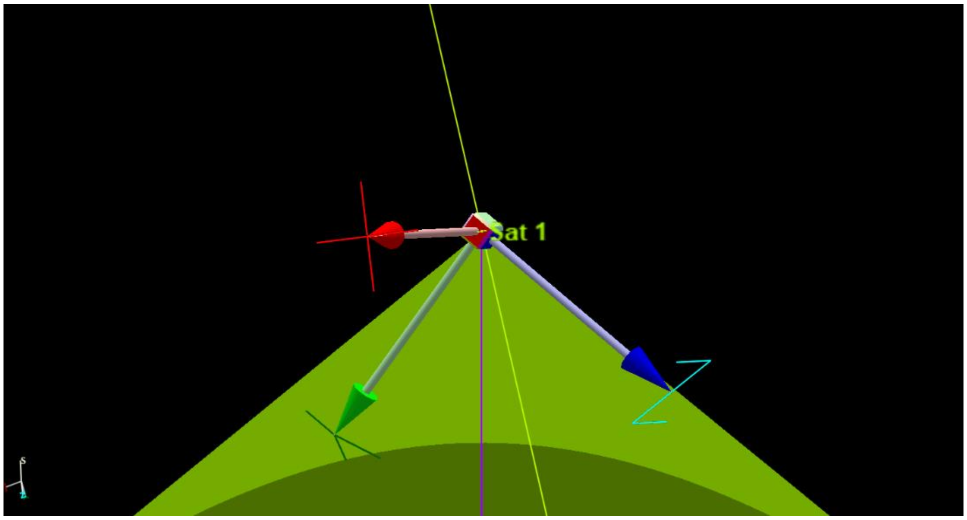

Figure 2-4: Sat1 SBM 3D File Surface Based.

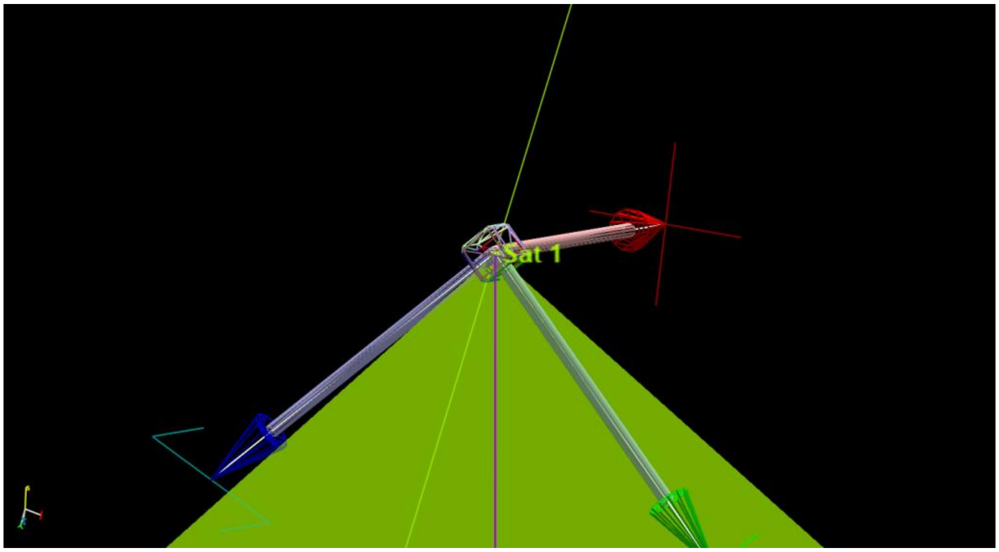

Figure 2-5: Sat1 SBM 3D File Wire Frame.

The Solar Panel 3D Model [+X, +Y, +Z, −X, −Y, −Z] structures were designed using the SOAP 3D Model ID ‘sat_gps_iir_m.sbm’ for its ‘Solar Arrays’ primitive files to attach to the Solar Panel [+X, +Y, +Z, −X, −Y, −Z] as the default node and the Axis Solar Panel [+X, +Y, +Z, −X, −Y, −Z] as the default coordinate system. The Solar Arrays primitive files contained *backface* and *shaded* features to display in the simulation. The Solar Panel 3D Models were designed independently from the satellite reference platforms and attached to *Solar Panel Platform* and *Solar Panel theta, phi Relative Platform(s)* after the wire frame visualization displayed where the location from which the platform center reference originated.

The Sat1 SBM 3D File Center Reference, shown in Figure 2-6, displays the platform’s center reference axis inside the ‘misc_triad.sbm’ 3D Model structure. Learning that the available SOAP 3D Model structures serve solely as a visual aid to the visualization study, the coordinate system objects were critical for the solar panel model developments and solar power calculations.

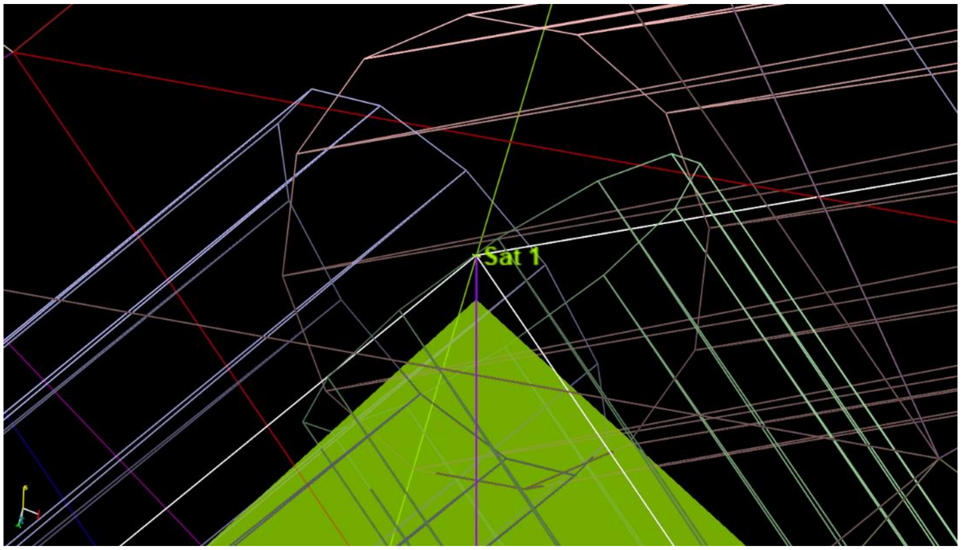

Figure 2-6: Sat1 SBM 3D File Wire Frame Center Reference.

Platform Coordinate System

The Reference Platforms Satellite 1–4 comprised of the *Slew Coordinate System (CS)* labeled as “pALL Slew” for the CS ID. The pALL Slew CS is one that is pointed and oriented according to a timed sequence of existing Coordinate Systems. As shown in Table 2.9, time offsets with corresponding pointing directions point to defined locations that could be modified in the SOAP environment. For the visualization study, the pointing directions are defined for the pALL Slew, Slew Coordinate System.

Table 2.9 CS ID pALL Slew

Name		**Value**
Year		2020
Month, Day, Hour, Minute, Second		12, 7, 14, 42, 0
	Time Offset (s)	**Pointing Direction**
1	0	NDR Sat1
2	127.17	NDR Sat1
3	137.171	pRNF Ptg
4	671.81	pPND Ptg
5	681.81	NDR Sat1
6	2383.9	NDR Sat1
7	2393.9	pCNP Ptg
8	3017.33	pCNP Ptg

Solar Panel Coordinate System

Modeling of the Solar Panels [+X, +Y, +Z, −X, −Y, −Z] of the Small Satellite Platforms Sat1–4 presented coordinate system visualization and analyses challenges. Since the satellite models are not monolithic, they contain surfaces whose positions must be articulated differently than the main body of the satellite, such as the solar panels. The solar panels had to be assigned their own coordinate systems to incorporate the satellite platforms slewing maneuvers and 3D Models, as shown in Tables 2.10–2.11. Additionally, the model surface from the leveraged 3D models were being treated as visible from both sides for each geometry face. The following had to be fixed to treat each geometry as a fixed solar panel face on the body of the slewing satellite.

Table 2.10 CS ID Axis Solar Panel [+X, +Y, +Z, −X, −Y, −Z]

Pointing Axis	**Direction or Reference**
Reference Axis: Theta/Phi Pointing Axis: [+X, +Y, +Z, −X, −Y, −Z]	CS: pALL Slew Theta: 0 deg Phi: 0 deg
Orienting Axis	**Direction or Reference**
Reference Vector: BCI Velocity Vector Oriented Axis: [+X, +Y, +Z, −X, −Y, −Z]	Earth

Table 2.11 CS ID To Solar Panel [+X, +Y, +Z, −X, −Y, −Z] theta, phi

Pointing Axis	**Direction or Reference**
Reference Axis: Platform Pointing Axis: [+X, +Y, +Z, −X, −Y, −Z]	CS: Solar Panel [+X, +Y, +Z, −X, −Y, −Z] theta, phi Theta: 0 deg Phi: 0 deg
Orienting Axis	**Direction or Reference**
Reference Vector: Theta/Phi Oriented Axis: [+X, +Y, +Z, −X, −Y, −Z]	.Sun Nadir

The Solar Panel Model [+X, +Y, +Z, −X, −Y, −Z] coordinate systems used the Basis Coordinate System type. The Basis Coordinate System allows the user to define the pointing axis and the orientating axis. To define the normal vector for each solar section plane, the reference axis θ(theta), ϕ(phi) was directed to point from the *pALL Slew* coordinate system reference. In addition, the orienting axis referenced the Body Centered Inertial (*BCI) Velocity Vector* oriented at the specified axis from the Earth reference.

The pointing axis and the orienting vector origin required the coordinate system to be referenced to the host platforms, *Solar Panel theta, phi Relative Platform(s)* to incorporate the To Solar Panel [+X, +Y, +Z, −X, −Y, −Z] theta, phi CS referencing SOAP's *Sun Nadir* CS for the solar calculations discussed in Chapter 3. The default coordinate systems provided in SOAP are named ". <.body>CR" for planetary bodies, shown in Table 2.12.

Table 2.12 CS ID .Sun Nadir

Pointing Axis	**Direction or Reference**
Reference Axis: Nadir Pointing Axis: Z	CS: Sun
Orienting Axis	**Direction or Reference**
Reference Vector: Theta/Phi Resultant: Y	.SunCR
CS ID .SunCR Pointing Axis: X and Oriented Axis: -Y	

The display of the axis for the pALL Slew coordinate system is provided in the Sat1 SBM 3D File +X and +Y views in SOAP, shown in Figure 2-7 and Figure 2-8.

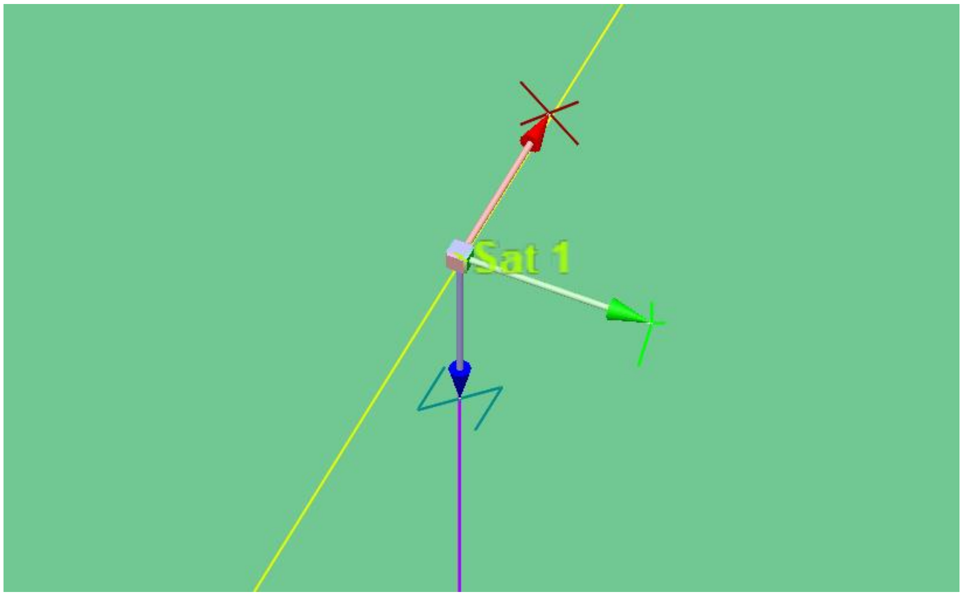

Figure 2-7: Sat1 SBM 3D File +X View.

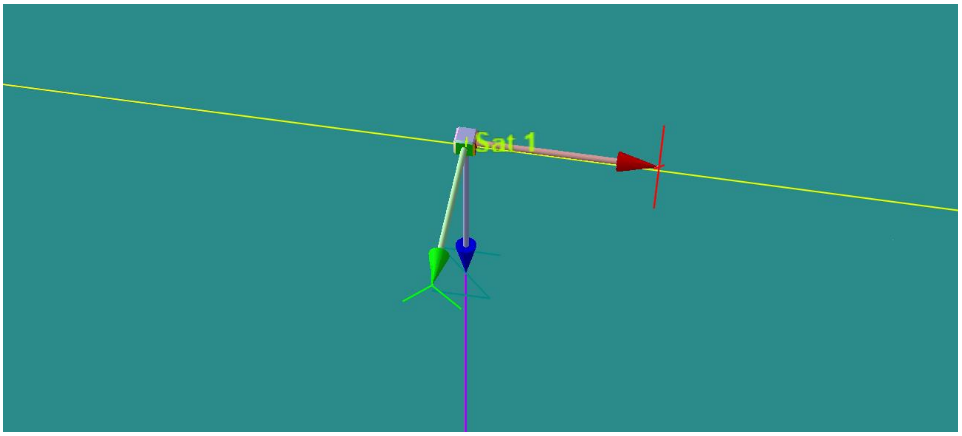

Figure 2-8: Sat1 SBM 3D File +Y View.

The Reference Platforms Sat1–4 all travel in track +X direction and start up in the following position pointing nadir to Earth. The pALL Slew axis during a simulation run slews according to the defined pointing directions and at the poles. Using the display axis feature assisted with the design of each coordinate system to verify the pointing and orientating axis for each theoretical solar section on the body of the satellite. Additionally, it provided visual verification for the camera and sun sensor access points discussed in the next section.

Platform Sensor

The payload of Reference Platforms Sat1–4 consists of camera and sun sensor objects defined in SOAP, as shown in Tables 2.13–2.15. SOAP allows for normal and regional sensor types to be defined for the simulation scenarios.

Table 2.13 SunSensor [+X, +Y, +Z, −X, −Y, −Z]

Name	**Value**
Coordinate System	.Sun Nadir
Shape	Hemispherical
Host Platforms	Solar Panel [+X, +Y, +Z, −X, −Y, −Z] Solar Panel [+X, +Y, +Z, −X, −Y, −Z] theta, phi
Target Platforms	Sun
Analysis	Sat Sun
Constraints	Host Sunlit Constraint Target Sunlit Constraint

Table 2.14 Camera [Sat1, Sat2, Sat3, Sat4]

Name	**Value**
Coordinate System	.pALL Slew
Shape	Rectangular
Host Platforms	[Sat1, Sat2, Sat3, Sat4]

Table 2.15 FOV [Sat1, Sat2, Sat3, Sat4]

Name	**Value**
Coordinate System	.Earth Nadir
Shape	Simple Conical [Max Half Cone 45-64 deg]
Host Platforms	[Sat1, Sat2, Sat3, Sat4]

Normal Sensor types with the geometry shape of *Simple Conical* were defined for Field of View (FOV) test captures of 45–64 degrees in reference to the *Earth Nadir* predefined coordinate system, shown in Figure-2-9 and Figure 2-10. The Camera objects use the geometry shape of *Rectangular* with full angular width of 10 degrees and full angular height of 5 degrees in reference to the pALL Slew coordinate system.

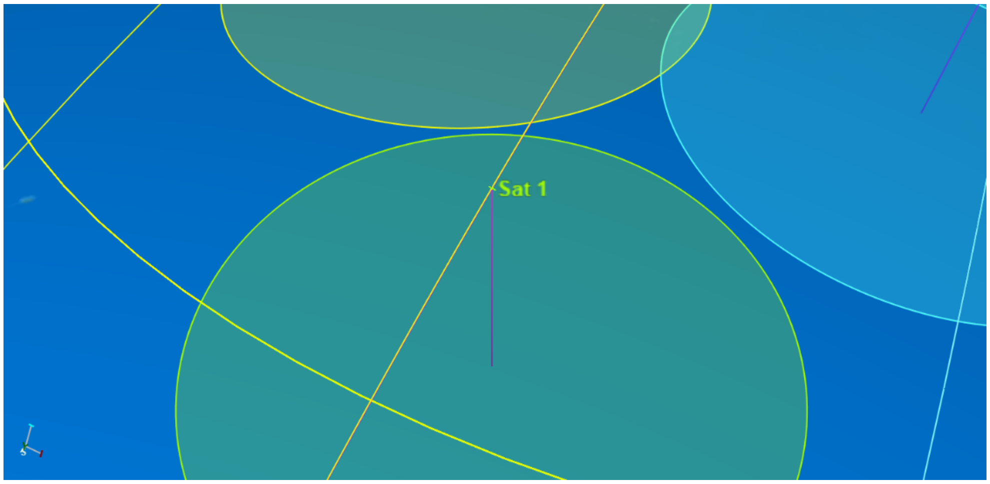

Figure 2-9: Sat1 SBM 3D File Nadir View.

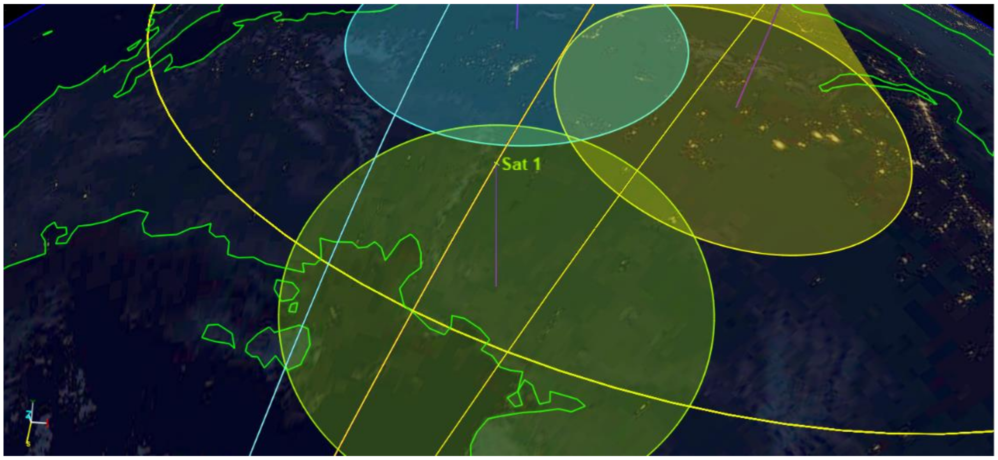

Figure 2-10: Sat1 SBM 3D File Nadir Night View.

The Camera sensor footprints can be observed in Figure 2-11. The Sun Sensor objects use the geometry hemispherical shape in reference to the Sun Nadir predefined coordinate system for the *Platform Sat Sun* analysis discussed in the next chapter. The SOAP sensor object advanced options allow for simulation constraints to be implemented, the Sunlit Constraint was enabled for the Platform Host and Platform Target. The target platform defined was the SOAP Sun model for the *SunSensors*.

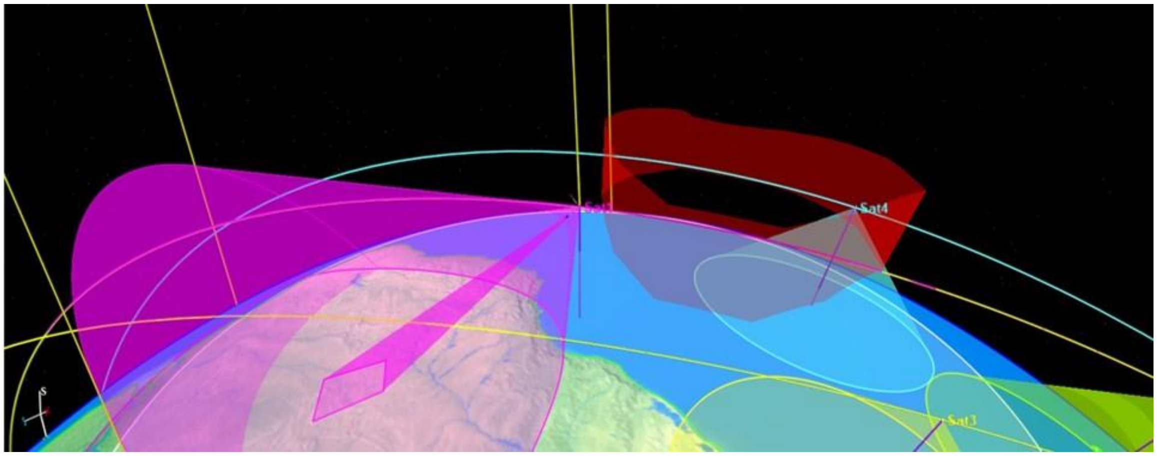

Figure 2-11 Sat1 Hemispherical Sensor Shape

Chapter 3

ANALYSIS OF SOLAR PANEL SOLAR IRRADIANCE

A solar power generator model for power consumption during an eclipse and sunlight period of orbital dimensioning object Sat1 was created. To estimate the available energy profile that will be available to the cognitive agents, it is important to evaluate the behavior of the electrical power system (EPS) for the analysis and the design, to provide reliable power to the satellite and satisfy subsystem requirements. The electrical power system consists of three subsystems: power generator, power storage, and power distribution [Wertz, 1999]. This chapter focuses on the solar power generator simulation model.

The Sun

SOAP nominally uses orbital prediction models for the Sun based on the Aerospace “ASTROLIB” software library. The values used in SOAP Sun propagation are obtained from [Bayliss, 1971] and the output of the propagator is the position of the Sun in ECI coordinates. Note that the Sun is considered a planet in SOAP for practical purposes.

Solar Eclipse

A satellite is said to be in eclipse when the Earth prevents sunlight from reaching it, which is when the satellite is in the shadow of the Earth or there is no line of sight between the Sun and the satellite [Vallado, 2001]. During a full eclipse, a satellite receives no power from its solar array, and it must operate entirely from its batteries. Batteries are designed to operate with a maximum depth of discharge; different battery types allow different percentage depths of discharge. If the battery is discharged below its maximum depth of discharge, the battery may not recover to full operational capacity once recharged. Therefore, the depth of discharge sets the power drain limit during eclipse operations. For example, nickel–hydrogen (NiH_2) batteries can operate to about a 70% depth of discharge and recover fully once recharged.

Eclipse is a design challenge, as not only is the main power source withdrawn (the Sun) but also the rapidity with which the satellite enters and exits the shadow can cause extreme changes in both power and heating effects over short periods. Figure 3-1 illustrates when the satellite is in the umbra (in eclipse), no line of sight exists between it and the Sun, where R_E is the radius of the Earth.

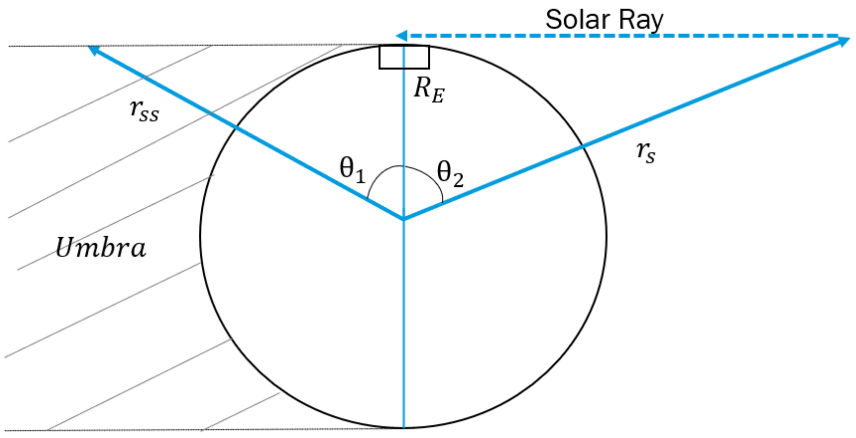

Figure 3-1 Parallel Solar Rays

If the position, at the edge of the cylindrical umbra, of the Satellite System, $\overrightarrow{r_{ss}}$, and the Sun, $\overrightarrow{r_s}$, is known, it can be verified if the satellite is in eclipse. The perpendicular line between the central point and the line-of-sight vector determines the two angles, θ_1 and θ_2 , which defines the transition point from sun to shade [VanOutryve, 2008], i.e.,

$$\theta_1 = \cos^{-1} \frac{R_{\mathrm{E}}}{|\overrightarrow{r_{\mathrm{ss}}}|} \tag{3.1}$$

$$\theta_2 = \cos^{-1} \frac{R_{\mathrm{E}}}{|\overrightarrow{r_{\mathrm{s}}}|} \tag{3.2}$$

Additionally, if the actual position and not the position at the edge of the cylindrical umbra of the satellite and the Sun are known, the angle, θ_{actual}, explains when the satellite is in eclipse, $\theta_{\text{actual}} > \theta_1 + \theta_2$, or in sunlight, $\theta_{\text{actual}} < \theta_1 + \theta_2$, with θ_{actual} defined as [Vallado 2001]

$$\theta_{\text{actual}} = \cos^{-1}\left(\frac{\overrightarrow{r_{\mathrm{ss}}} \cdot \overrightarrow{r_{\mathrm{s}}}}{|\overrightarrow{r_{\mathrm{ss}}}|\,|\overrightarrow{r_{\mathrm{s}}}|} \right) \tag{3.3}$$

Satellites can suffer many of their component failures under sudden stress situations. Therefore, eclipse periods are monitored carefully by ground controllers, as this is when most of the equipment failures are likely to occur. SOAP allows the user to construct analysis types to report logical and numeric results, including the *Eclipse Analyses* which is a collection of four eclipse conditions (Annular Eclipse, Any Eclipse, Partial Eclipse or Total Eclipse) that can be set up with respect to a platform. In this study, SOAP displayed eclipse access points for each satellite.

Figure 3-2 illustrates the *Number of Accesses* for Satellite 1, which records the number of discrete times or accesses between Satellite 1 and Ground, Target in View, Sun in View, and Eclipse periods over the time span specified by the user. Figure 3-3 illustrates a visual example of the Satellite Cluster receiving *Sun Access* that is represented in Figure 3-2 as *Sat1 Sun*. Furthermore, additional built-in *Eclipse Magnitude* and *Eclipse Obscuration* SOAP analyses can be computed to either measure how much of the Sun is being concealed by the Moon as seen from the location of the platform satellites or compute the percentage of an occulted body that is blocked by an occulting body.

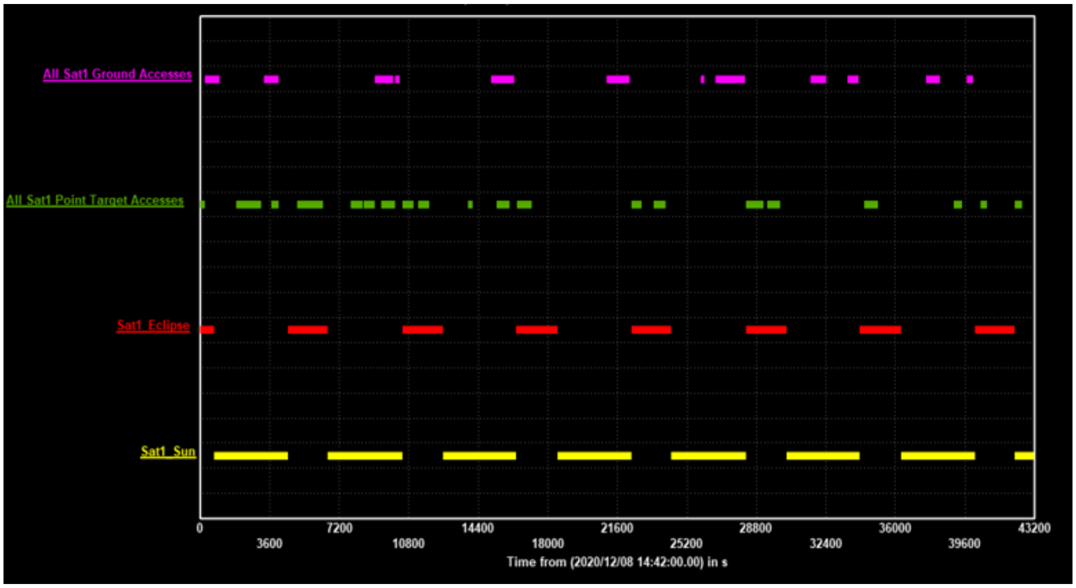

Figure 3-2 Satellite 1 Access Data

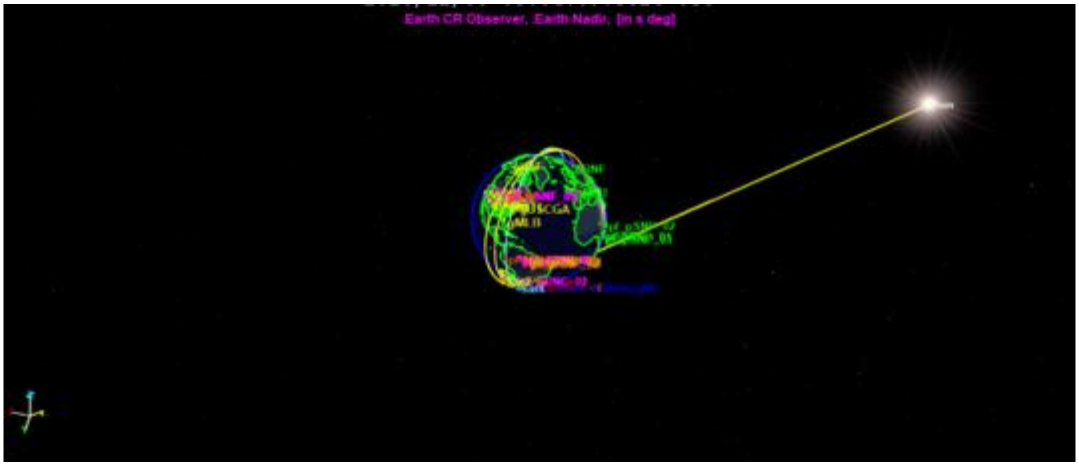

Figure 3-3 Sun Access to the Satellite Cluster View

Solar Power Generator

To estimate the energy budget, we need to know the orbit-average power requirements during daylight and eclipse generated by the Solar Panel object. In Sat1's solar section, assuming the solar cells are mounted on all surfaces across each side of the platform, the solar cell sets, and battery charge regulators are represented as an embedded solar section, Solar Panel object. The scenarios created in SOAP were assumed for solar panel sizing and based on the leveraged functionalities available in SOAP.

The parameters that are related to the solar sections power generation include the Sun vector, normal vector, incident angle, and solar cells. SOAP has been used as the software to model and run the simulation due to its ability to incorporate these parameters. The SOAP results and 3D visualization provide the satellite orientation in space with respect to the SOAP Sun model. The predefined SOAP Sun model provides the sunlight vector used for the calculations of power generated. Since the satellite has a slewing coordinate system, the slew angle of the platform was used for the incident angle calculation. Additionally, the solar constant had to be defined for the power out expression. The orbital parameters that are related to the solar panel illumination intensity include the Sun incident angles; eclipse period; duration of illuminated and shadow areas; electrical characteristics of solar cells; their temperature and state of health; and concentration of solar energy. The power of the solar sections also depends on the illumination, i.e., the amount of solar power that reaches the solar cell per unit area. This energy is determined by the orientation scenario (and attitude control method) of a satellite since it depends on the angle between the direction of the sunlight and the normal to the solar section surface.

Platform Sun Analysis

The SOAP logical *Sat Sun* analysis is a *Target in View* type with the following parameters: SunSensor [+X, +Y, +Z, −X, −Y, −Z], Host Platform [Sat1, Sat2, Sat3, and Sat4], and Sun Target Platform to calculate the Sun in view. The logical analysis range is [0: False, 1: True] and the simulated real-time result is used in a variety of defined expressions for the solar panel solar irradiance analysis. The Power [+X, +Y, +Z, −X, −Y, −Z] preliminary expression definition includes the parameters of solar array maximum power multiplied by the cosine sun angle with respect to the *Sat Sun* analysis. The Solar Array Maximum Power and Solar Constant, G_{SC}, were defined as expressions in SOAP. The Sun Angle represents the solar panel θ and ϕ angles. The Solar Constant flux density is a measure of the total radiation energy received from the Sun and, at extreme distances, it can be taken as a constant with the values of approximately 0.1353 W/cm^2 in the vicinity of the Earth [Wertz, 2011].

Table 3.1 Solar Cell Characteristics

Parameter	**Value**	**Units**
Solar Constant (G_{SC})	0.1353	W/cm^2
Solar Cell Size (SA) (1.975 × 2.025 cm)	26.6	cm^2
Solar Cells per String per Spacecraft Side (SC)	7	cells
Solar Cell Efficiency at Reference Temperature at 28 °C (C_{eff})	0.28	unitless
Power per String (Sun Normal to Array)	7.05	W

The SOAP *Beta Angle* analysis measures how much the Sun is out of the orbital plane of the specified platform. It represents the complement of the angle between the orbital plane and the vector from the Sun. The Solar Beta Angle, β, determines the percentage of time that a LEO Satellite spends in direct sunlight absorbing energy, shown in Figure 3-4 [Hassman, 2003], and is given by

$$\beta = \sin^{-1}[\cos(\Gamma)\sin(\Omega)\sin(i) - \sin(\Gamma)\cos(\epsilon)\cos(\Omega)\sin(i) + \sin(\Gamma)\sin(\epsilon)\cos(i)] \tag{3.4}$$

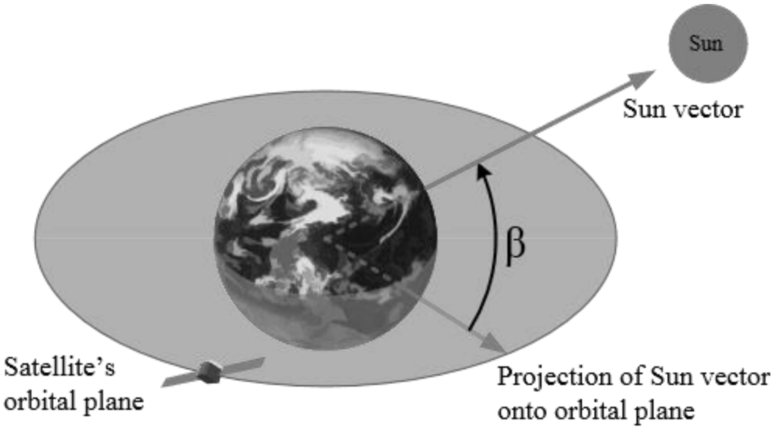

Figure 3-4 A depiction of the solar beta angle of a satellite. [Image credit: Fomirax/Wikimedia Commons]

The position of the Sun on the celestial sphere along the ecliptic, Γ, also commonly known as the ecliptic longitude of the sun, L_s, contributes to the relative length and intensity of the seasons. The ecliptic is the plane of Earth's orbit around the Sun. The Right Ascension of Ascending Node (RAAN), Ω, specifies the location of the ascending node along the celestial equator. The ascending node represents where the satellite motion is toward the positive ECI Z axis in SOAP. The right ascension is the angle about the Earth's rotational axis measured in the equatorial plane from the ECI X axis positive towards the ECI Y axis in SOAP. The orbit's inclination, i, and RAAN are properties of the satellite's orbit. The SOAP Earth object is tilted approximately 23.5° with respect to the ecliptic plane. The average tilt in SOAP is called the *Mean Obliquity of the Ecliptic* obliquity, the constant value of 2.344306000e+4 degrees was defined and obtained from Melbourne [1968] and Bayliss [1971]. The obliquity of the ecliptic, ϵ, is the angle between the ecliptic and the celestial equator in Eqn. 3.4. Moreover, to solve for the power per string, i.e.,

$$\text{Power per String } (\beta = 0°) = G_{\text{SC}} \times C_{\text{eff}} \times \text{SC} \times \text{SA} \qquad (3.5)$$

Where the β angle equal to 0° is for the maximum amount of time the LEO Satellite can spend in the Earth's shadow, similarly for when the Sun is normal to the solar array. Multiplying the solar cell characteristics by the solar constant provided in Table 3.1 gives the power per string when the Sun is normal to the solar array. From Eqn. 3.5 we have the solar array maximum power defined to be approximately 7.05 W.

The parametric study performed for the Solar Intensity (SI) power out expression defined in SOAP accounts for the satellite slewing coordinate system capturing the varying θ and ϕ angles in rotation. The SunAngle [+X, +Y, +Z, −X, −Y, −Z] position analysis was defined as a Cone Angle [−360 to 360 degrees] type that referenced the *To Solar Panel* [+X, +Y, +Z, −X, −Y, −Z] θ, ϕ coordinate system defined previously in Chapter 2, Solar Panel [+X, +Y, +Z, −X, −Y, −Z], and Sun Target Platform. The *Cosine Sat Sun* expression multiplies the cosine of SunAngle [+X, +Y, +Z, −X, −Y, −Z], *Sat Sun* 'Sun in View', and the cosine of SunAngle [+X, +Y, +Z, −X, −Y, −Z] greater than logical 0.0 to provide the result for the Power [+X, +Y, +Z, −X, −Y, −Z] calculation. Hence, the expressions for SI Eqn. 3.6 and Power Out Eqn. 3.7 are

$$\mathrm{SI} = \cos(\mathrm{Sun\ Angle}) \times \mathrm{Sun\ in\ View} \times (\cos(\mathrm{Sun\ Angle}) > 0.0\,) \tag{3.6}$$

$$\mathrm{Power\ Out} = \mathrm{Solar\ Array\ Maximum\ Power} \times \mathrm{S} \tag{3.7}$$

The scenario mission does not have a solar tracking mechanism to orient the platform body to its maximum solar illumination and assumes the direction of flight to be in the +X in-track axis and the slew orientation along +Z axis pointing nadir. The Solar Panel objects had to be defined in SOAP with their own coordinate systems to segment the normal vectors on each face from the platform's reference slewing coordinate system. The placement of static Solar Panel object [+X, +Y, +Z, −X, −Y, −Z] on all the exterior faces of the satellite ensures that there is at least one face pointing towards the Sun.

As can be seen from Figure 3-5, successful captures of the solar panel illumination intensity on each solar panel face are present when the solar panel objects individually pertain to their own coordinate systems oriented around the satellite slewing maneuver.

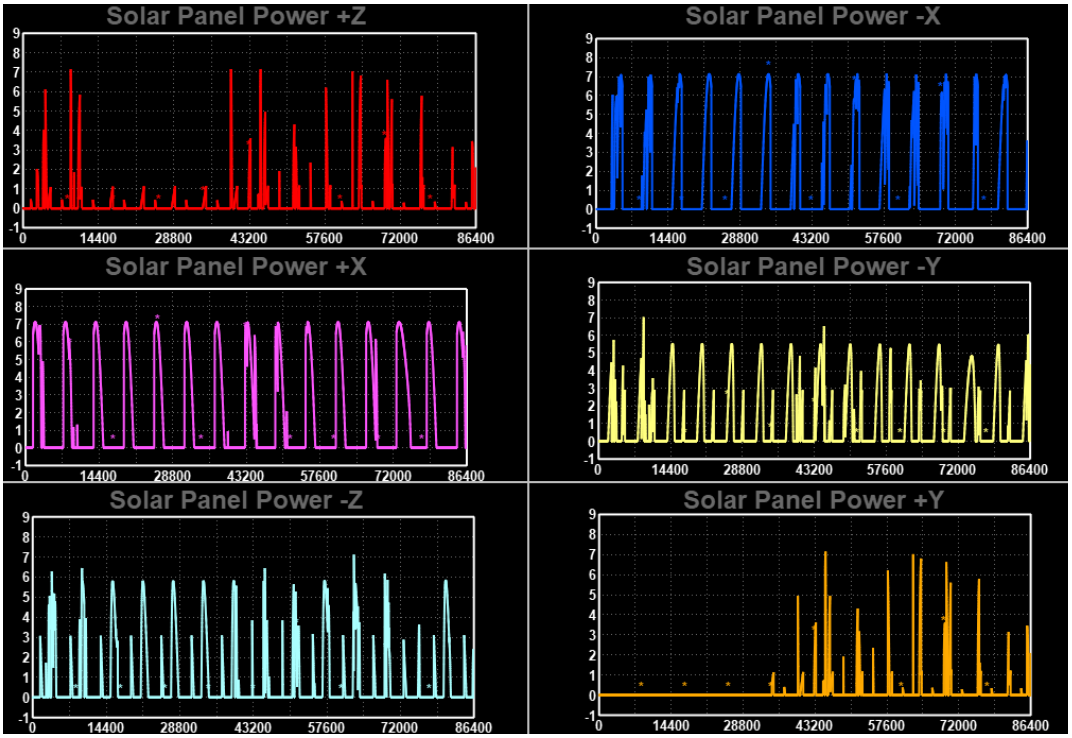

Figure 3-5: Solar Panel Power Out plots show the power peaks and eclipse cutoffs for each Satellite Solar Panel Face [+X, +Y, +Z, −X, −Y, −Z] (y axis is in W)

The analysis performed demonstrated that all sides of the satellite are illuminated by the Sun at some point during the defined circular polar orbit, as shown in Figure 3-6. Therefore, all sides were included in the Power Out total. The solar cell efficiency, inherent degradation, and the lifetime degradation are all percentages that scale the generated power. The solar cell efficiency is a measure of how much of the energy of the incident sunlight is converted to usable power. For the types of space solar cells commonly used today, efficiencies of roughly 27% to 30% are typical [Socolovsky, 2017].

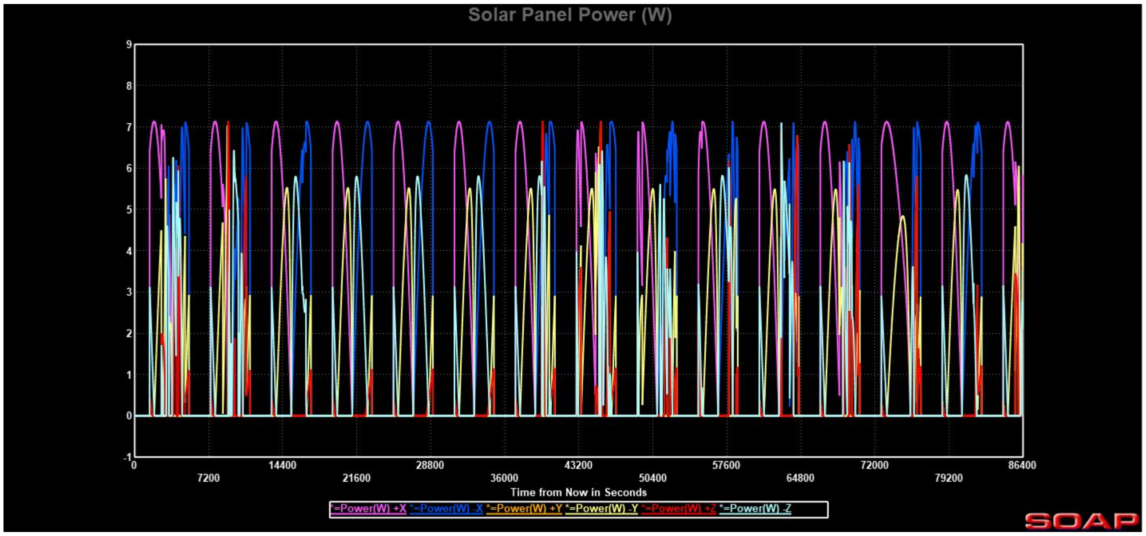

Figure 3-6: Solar Panel Power (W).

The solar panel power total for Satellite 1, shown in Figure 3-7, displays the power peaks for the summation of each Solar Panel [+X, +Y, +Z, −X, −Y, −Z] platform on Satellite 1 with eclipse cutoffs provided by the *Sun Analysis* accesses.

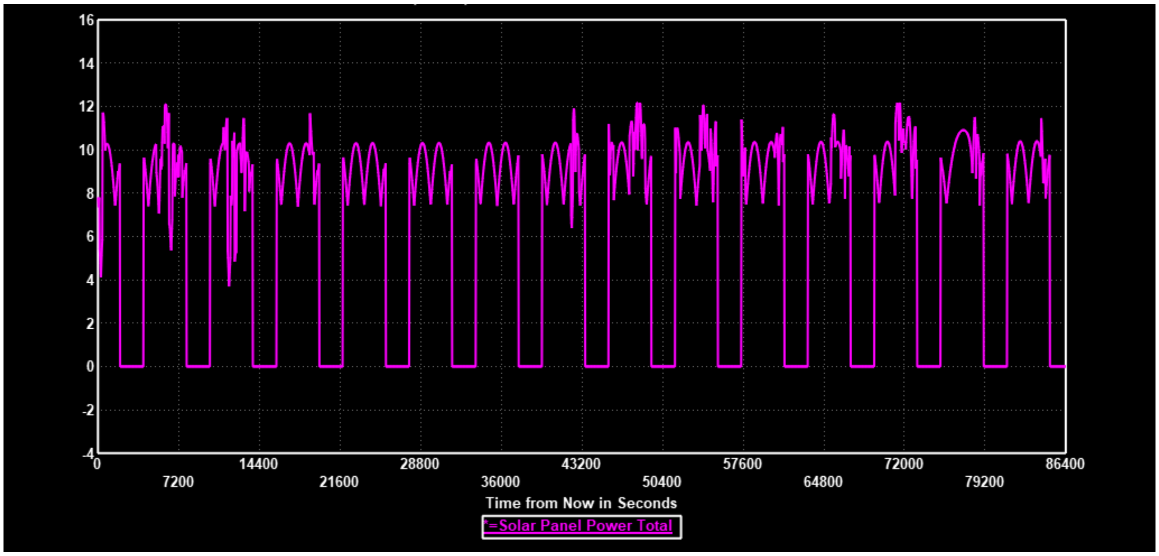

Figure 3-7 Solar Panel Power Total for Satellite 1

To estimate the energy budget, we need to know the orbit average power generated by the solar panel platforms during daylight and eclipse. The orbital parameters that are related to the solar panel illumination calculations are provided in Table 3.2, and the orbit-average energy output can be calculated via

$$\text{Sunlit Orbit Fraction (SOF)} = \frac{(\text{Satellite Orbit Period} - \text{Eclipse Minutes per Orbit})}{\text{Satellite Orbit Period}} \tag{3.8}$$

$$\text{Orbit Average Power (OAP)} = \text{Avg. Sunlit Power } \times \text{SOF} \tag{3.9}$$

$$\text{SA Orbit Average Energy Output } = \text{Avg. Sunlit Power} \times \text{SOF} \times \text{Period} \tag{3.10}$$

Table 3.2 SOAP Scenario Orbit Properties

Parameter	**Value**	**Units**
Semimajor Axis	7066.60	km
Eccentricity	0.0024145	unitless
Period	98.53	min
Inclination	88.89	degrees
Eclipse Minutes per Orbit	32.29	min
Sunlit Orbit Fraction	0.63	unitless

The power out profile scenario results show the average power during a whole orbit period to be about 4.5 W, and the solar array orbit average energy output will be 438 W·min. The calculation results from the solar power generator model are an estimate of the total generated power of the solar section of the satellite systems.

Chapter 4

SYSTEM DESIGN AND CAPABILITIES

Exploring Software Capabilities

In this study, SOAP is used as the visualization and verification tool to verify the results of the satellite elements in orbit. SOAP provides the essential simulation, modeling, visualization, and analytical capabilities. Performing a simulation within SOAP demonstrated that the software supports the visualization study by providing a complete overview of the system while accumulating knowledge to assist with planning space missions. It is critical to minimize performance margins by using sophisticated modeling, visualization, and simulation software. SOAP is an effective tool that provides opportunities for refining and supporting rapid development of the satellite systems.

The SOAP environment contains several functions required to do the verification process for a small satellite battery management system. The next level of implementation will be to design and develop a SOAP battery emulator model for the complete power profile. The results will include specified minimum usable energy, capacity, and battery types required by the system being designed. The SOAP battery emulator model will include additional visualization and analysis functions to pass data between SOAP and external applications, such as MATLAB. The MATLAB Interface analysis feature in SOAP can utilize output from MATLAB Arrays (the “.m file”). The results will include specified minimum usable energy, capacity, and battery types required by the system.

An essential component of nearly every small satellite is the energy storage device [Knap, 2020]. When there is no radiation received from the Sun, the energy collected by the satellite’s solar cells and stored in batteries provide power to the system. Several types of batteries exist, including a collection of different properties and chemistry types. There are advantages and drawbacks for each type. Lithium–Ion batteries have higher per-cell voltage than NiMH (Nickel Metal Hydride) and NiCD (Nickel Cadmium) batteries, have high energy densities [Day, 2004], and are easy to produce in prismatic form [Jeppesen & Thomsen, 2001] rather than cylindrical packs. On the downside, they are more expensive, require specialized charging circuitry, and have a slightly shorter life cycle [Lim, 2018].

Small satellites typically use commercial off-the-shelf (COTS) battery technologies. Ongoing research to further generalize testbeds for certification of COTS batteries for small satellite systems allows satellite missions to determine the battery demands needed to evaluate operating margins in the space environment. Certification tests for the solar cells and packs can include electrical cycling characterization, overcharging/discharging, external shorting, vibrational excitation, and exposure to vacuum [Cameron, 2015].

Implementing an interface to include the following electrical characteristic inputs would allow the current SOAP visualization study to not only dimension the energy storage system but establish strenuous operating conditions that ensures the batteries selected perform appropriately when in operation. Future work will include further validation against AGI System Took Kit (STK) Solar Panel tool and real data from small satellite mission components.

Chapter 5

CONCLUSIONS

The satellites were dimensioned and modeled using the visualization software SOAP. The important elements of the satellites are the solar panels, sun and camera sensors visualized and verified using SOAP. The power profile results need to be verified after the satellite environment system transitions to interface with hardware module components. The power generation calculation shows that the power generated by the solar panels are of an average of approximately 4.5 W and the total energy generated during an orbit will be 438 W·min.

The design of a battery management system begins with understanding, estimating and modeling the orbit-average power during daylight and eclipse that a small satellite solar section will generate during its mission. Successful models were created and analyzed for the power estimation expected for the small satellite cluster, as well as the development of solar panel models. There is still work to be done to ensure proper design for reliability of the small satellite cluster in performing all mission requirements, including a more detailed battery model in SOAP and MATLAB where critical components are added to simulate additional electrical characteristics. Additionally, orientation designs for the solar arrays can provide the capability to generate more power for the weight and size which the small satellite occupies [McGill, 2018].

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