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Dear Sir:

This report, entitled "Nanosatellite Mission Power Analysis", was prepared as my 2B Work Report for the Canadian Space Agency. This is my third work term report and thus in fulfillment of the course WKRPT 300. The purpose of this report is to investigate the issue of a small satellite's power availability and to supply a set of engineering recommendations as to whether the project can proceed with sufficient power, or whether there need to be more solar cells added in order to provide additional power.

The Canadian Space Agency is an aeronautics and exploration agency that was established in 1989 under the Canadian Space Agency Act. Its five key functions are separated into Space Science, Space Technologies, Space Operations, Space Programs, and the Canadian Astronaut Office. The agency's main mandate is to ensure that space science and technology provide social and economic benefits for Canadians.

The Space Technologies Department, in which I was employed, was put in place in order to develop innovative and emerging technologies and support Canadian industries in maintaining a competitive edge on the international level. More specifically, within this department was the spacecraft engineering group, whose main responsibility was Research and Development in the areas of spacecraft control systems, space materials and structures, space dynamics, and spacecraft and planetary exploration robotics. This group was headed by George Vukovich, and involved various long-term and short-term projects.

I would like to thank Mr. Balaji Shankar for teaching me our group's mission objectives and details. Furthermore, I would like to acknowledge Mr. Sudarshan Martins for answering the majority of my inquiries during the learning process and the writing of this report. Also, I wish to thank Mr. Martins for double-checking my report spelling, and proofreading it with me. Also, I would like to thank Professor J.A. Barby for providing an online template and guideline for this report. I hereby confirm that I have received no further help other than what is mentioned above in writing this report. I also confirm this report has not been previously submitted for academic credit at this or any other academic institution.

Sincerely,

Goran Vlacic
ID 20201180

Canada

CONTRIBUTIONS

The team I worked in was of an average size relative to the other project teams within the Canadian Space Agency. It consisted of approximately 25 core people. The discrepancy in the size is due to constant increases and decreases in the number of contributors. The assistance of test engineers is sometimes needed when there is nobody else in the team with the level of experience in handling and assembling components in a clean room environment. Also, there is an undergraduate student position, and several masters and doctorate student positions that are being vacated and refilled depending on availability. An important part of the team that should not be left out is the group of 3 JAXA (Japanese Aerospace Exploration Agency) engineers who integrate themselves into the team by holding weekly videoconferences and visiting every two months.

The team's main goal is to successfully complete the design, testing, assembly and launch of a nanosatellite in cooperation with JAXA. A nanosatellite design is used for this project because it can be built with a reasonable cost, and within a short development time. The cost and time savings allow for more experiments to be carried out and thereby create three main objectives for the mission. The objectives include completing Autonomous Formation Flight with the use of atmospheric drag alone (meaning no propulsion is being used), demonstrating on-orbit navigation using a GPS receiver and an inter-satellite RF link, and finally, demonstrating on-orbit use of a Miniature Far-Infrared Radiometer. There are also, two secondary goals of the project, and they consist of strengthening the relationship between JAXA and the CSA, and providing hands-on training to engineers working at both agencies.

My tasks included, but were not limited to, assessing the mission's critical power scenarios, modeling satellite orientations in various programs, and approving the readiness level of the satellite's power system for launch. One of my specific tasks consisted of analyzing the project's power budget. This task involved calculating the power generation changes throughout the satellite's orbit, and comparing them with the Electrical Power System's total power usage estimates. This task was carried out with the use of orbital mechanics textbooks, several satellite simulation programs, and with the help of experienced engineers with specializations in this field.

The relationship between this report and my job is that the final recommendations made in this report were the major goal of my work term. It was my task to devise a method, similar but not identical to previous ones, that would independently evaluate the mission's critical power scenarios and report as what design changes needed to be implemented if any. The bulk of the report explains the method used to analyze the problem and thus the work I had done in preparing my model. The end of the report presents results and recommendations which were used for both the purposes of writing this report and for use with the mission.

SUMMARY

The main purpose of this report is to investigate the issue of a small satellite's power availability by using a model to analyze its power generation, storage, and consumption throughout different mission scenarios. The report will supply a set of engineering recommendations as to whether the project can proceed with sufficient power, or whether there needs to be more solar cells added to provide additional power. The report first gives a background on the satellite's mission and then introduces the problem at hand; whether there will be enough wattage at all critical scenarios so as the satellite's battery does not deplete past specific values. The report then gives several quantitative criteria to assess the problem. The problem is modeled and analyzed with the help of a specifically created power budget tool, and the results of which are compared against the criteria.

The major points documented in this report are as follows. The first point is that there is an issue on the mission because it is unknown whether there will be enough power for the mission to be a success. The next point covered is that an engineering tool was created that can analyze this problem by computing the satellite's power generation, storage, and consumption. The last point is that conclusions can be drawn from the results of the tool, and recommendations can be made based on the conclusions.

The first major conclusion in this report is that the satellite's battery will not fully deplete at any point in the mission. The next major conclusion is that the satellite's battery does not reach a depth of discharge higher than the industry recommended maximum value. The final conclusion is that additional solar cells on the bottom of the satellite's drag panels would be beneficial.

The first major recommendation in this report is that a vital redesign, that would rearrange the satellite's bus structure and component placement, should not take place. It is then recommended within the report that it is not crucial to add extra solar cells if there is no room for them, but beneficial if there is room. The third and last major recommendation of this report is that the power budget tool should be used in the future to produce charts showing the benefit of specific numbers of solar cells if it is within the mission's financial constraints.

CONCLUSIONS

From the engineering analysis in the report body, it was concluded that the battery will not run out or reach an alarming depletion level, and that extra solar cells beneath the satellite would be beneficial.

In more detail the first conclusion in this report is that the satellite's battery will not fully deplete at any point in the mission. The results showed that even though there were times when the power consumption of the satellite exceeded the power generation, the battery still had enough stored charge to supply the satellite with power. The battery never ran out, and the mission was thus able to carry out all its objectives without any difficulties.

The second conclusion is that the satellite's battery does not reach a depth of discharge higher than the industry recommended maximum value. The results showed that the depth of discharge was never at 25% or above even during eclipses and when the satellite's panels were not fully deployed and the conclusion is that spacecraft engineering suggested battery levels have been maintained.

The final major conclusion is that additional solar cells on the bottom of the satellite's drag panels would be beneficial. Results showed that when extra cells were added to the bottom of drag panels where there is room for additional panels, the satellite generated more power than without them and thus adding cells would be positive from a power generation point of view.

RECOMMENDATIONS

Based on the engineering analysis and conclusions in this report, it is recommended that the satellite should not be redesigned, that solar cells not be added unless there is room, and that the student-created engineering analysis tool be used to further investigate specific additions.

The first major recommendation is that a vital redesign, that would rearrange the satellite's bus structure and component placement, should not take place. The satellite has been found to have sufficient power for survival in test cases. There should be no resources allocated towards rebuilding it.

The second recommendation is that it is not crucial to add extra solar cells if there is no room for them. The conclusions showed that it is not necessary, but is beneficial to add cells. So it is recommended to allocate time and resources towards investigating whether there is enough room anywhere on the satellite, especially beneath the drag panels, to accommodate for extra cells.

The last major recommendation of this report is that the power budget tool should be used in the future to produce charts showing the benefit of specific numbers of solar cells, if it is within the mission's financial constraints. The tool is still very useful, and should be put into action by entering anywhere from zero to as many solar cells that can fit on the bottom of the drag panels or anywhere else that the team finds to be suiting, that is if the project has enough money left over to afford more solar panels.

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1.0 INTRODUCTION

The Canadian Space Agency is an aerospace and exploration agency established by the Canadian Federal government under the Canadian Space Agency Act of 1989 [1]. Its central station is called the John H. Chapman Flight Centre and is located near the airport in the town of St-Hubert, just outside of Montreal, Quebec. It also has a several other offices across Europe and the United States to support work done with the European Space Agency and the National Aeronautics and Space Administration, as well as extra labs at the David Florida Laboratory in Ottawa, Ontario.

Most well known to the public are the Canadian Space Agency's (hereinafter referred to as the CSA) current contributions to the International Space Station: the Canadarm, the Canadarm2, and the recently launched Special Purpose Dexterous Manipulator (Dextre) [2]. The agency has also been developing satellites for the last five decades, and training astronauts for the last three. Its main mandate is "To promote the peaceful use and development of space, to advance the knowledge of space through science and to ensure that space science and technology provide social and economic benefits for Canadians" [3]. Under this mission statement all of the CSA's activities can be categorized into five key functions: Space Science, Space Technologies, Space Operations, Space Programs, and the Canadian Astronaut Office. Of these five, the Space Technologies function is the one involved in spacecraft build-up, experimentation, and engineering.

Space Technologies hopes to "be the functional centre for technical expertise within the agency" [4] as well as attempt to "ensure the development of space technologies to enhance Canadian industrial competitiveness and to support Canadian space programs" [4]. These mandates allow Space Technologies to be a formal department within the agency, which is then split up into Technology Management and Applications, Spacecraft Engineering, Spacecraft Payloads and Systems Engineering. Spacecraft Payloads deals with what needs to be placed onboard a craft but is not integrated into the structural design of it. Systems Engineering is in place for project management purposes and to ensure that space programs are successful in a cost and time effective manner. Technology Management and Applications is concentrated on the diffusion and commercialization of space technologies in Canada, and finally Spacecraft Engineering handles projects at the research and development level [4].

Some of Spacecraft Engineering's current projects include SCISAT-1, RadarSat, Mars Exploration, On-Orbit Robotics, Inflatable Structures, and many other endeavors [5]. SCISAT-1 and RadarSat are just a few of many earth observation satellites that the department is working on. The other projects listed above, are examples of new and old technologies that are constantly being tested for space readiness.

One of the smaller research satellite projects in Spacecraft Engineering is the JC2Sat - Japan Canada Joint Collaboration Satellite. As the mission title would suggest, this mission is in cooperation between the Japanese Aerospace Exploration Agency (hereinafter referred to as JAXA) and the CSA. The JC2Sat mission consists of two twin nanosatellites created for experimentation purposes. It will try to demonstrate formation flying in orbit without the use of a propulsion system [6]. As with all other satellites, these will have to be self-sustaining: generate, store, and regulate their own power. This power will then be used to carry out the mission's objectives.

This report provides an analysis of JC2Sat's power budget. It begins by providing a background of the JC2Sat mission, its design, and its status. Then, the report goes on to describe a power budget analysis tool that evaluates wattage generation, storage, and consumption figures. The main tasks at hand will be to first ensure that power will be available during all mission scenarios, and second to determine how many extra solar cells, if any, need to be added into design. Finally, the report summarizes the results of the analysis, draws conclusions from them, and makes recommendations as to what design changes need to be implemented.

The reader does not need to have a background in astrodynamics or orbital mechanics because all such methodologies are explained in detail within the report. However, since this report is being written for completion of a Nanotechnology Engineering curriculum requirement, the reader is assumed to have a foundation in band gap theory and semiconductor properties. Where there is previous knowledge required, background information and appendices are provided for the reader's benefit.

2.0 JC2SAT MISSION

The following section deals with the background of the JC2Sat Mission. The reader is first introduced to the reasons why the mission was designed, approved and is being carried out.

The objectives are clearly stated and similar missions performed in the past are used as a comparison to help the reader understand the current mission. JC2Sat's uniqueness is discussed later on, and a more detailed explanation of conceptual design and formation flight is given. Finally, the current mission status is presented because there is still work to be done, and changes to be made.

2.1 Similar Missions and Uniqueness

During the late 1980's Orbital Sciences Corp devised a global communication system based on a constellation of satellites; Orbcomm. Each satellite maintains a specific separation distance with its two neighbouring satellites through drag controlled formation flight. Currently Orbcomm has a total of 35 satellites flying in formation around an orbit approximately 300km above ground. An electric motor rotates Orbcomm's solar panels at different angles to increase or decrease the surface area exposed to atmospheric drag. However, Orbcomm possesses a gas propulsion system to initially park the spacecrafts on-station after successful launch [7].

Similarly, the JC2Sat mission will also use atmospheric drag to control the separation distance between its twin spacecrafts. However, unique from Orbcomm spacecrafts JC2Sat crafts will not have any motor to control its deployable panels, but rather computer triggered spring hinges. Also unique from Orbcomm, JC2Sat satellites shall use momentum wheels to orient itself in a fashion that will increase or decrease atmospheric drag. Note that the JC-X's deployable panels will be deployed once and be fixed for the rest of its mission life.

Structurally, the two spacecrafts are dissimilar. JC2Sat craft are Nanosatellites, while Orbcomm's are Microsatellites (designated by a weight classification, where the latter is heavier). Also, the JC-X has a rectangular form, while the Orbcomm has a round one.

Keep in mind, the key difference between the JC2Sat mission and every other satellite mission is that the JC2Sat does not have a propulsion system. It will attempt to, for the first time without propellant, carry out formation flight.

2.1 Conceptual Design and Formation Flight

During its life time the JC2Sat mission attempt to near its two satellites between 1km and 100m of each other. This maneuvering is called formation flight, control of the location and orientation of multiple spacecraft in orbit. The difficulty in doing this without a propulsion system is that no forces except gravity will be able to assist in maneuvering.

The satellite's use what is called a Bang-Bang method to approach each other. The first satellite is pointed down and drops closer to the earth, at which point in time its orbit speeds up ever so slightly in comparison to the other satellite because an orbiting body closer to its focus rotates faster (Kepler's Laws) [8]. After the first satellite gets slightly ahead of its own previous position, the second satellite is dropped down to the same level, and its orbit is matched, but the two satellites are now closer/further away then they previously were, depending on the maneuver being executed. Figure 2 gives a sketch of what both JC2Sat satellites bus structure look like, along with a labeling of each of the solar panel faces.

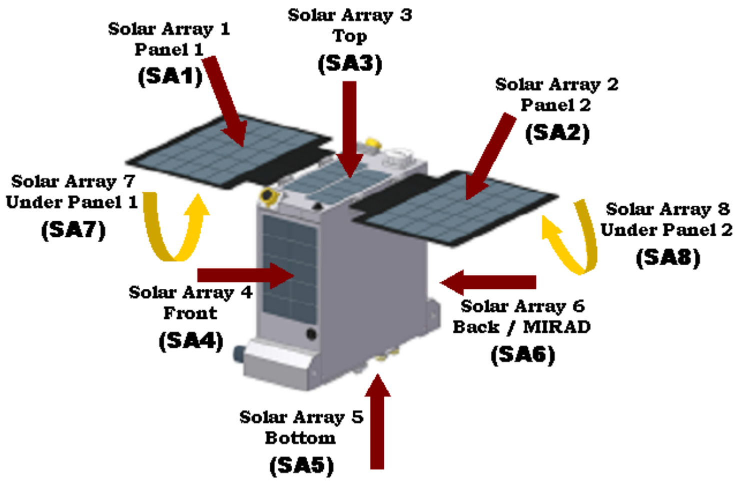


Figure 1: Single JC2Sat Spacecraft

Notice that Solar Arrays 7 and 8 are pointed to in yellow because they are beneath the deployable drag panels, and also because there may or may not be extra solar cells added there at all. Currently there are no solar cells in locations SA7 and SA8, but one of the issues that this report aims to resolve is whether there will be any cells added in these locations or not.

The mission's main objective is to maintain formation flight using the techniques explained, but as most other satellites have, JC2Sat posses a payload with the purpose of scientific research. The payload is independent of the structure and vital subsystems of the satellite, and a satellite can function without its payload. JC2Sat's payload is a Miniature Far Infrared Radiometer that will study the earth's atmosphere. The mission's and the satellite's bus structure and its payload are not of much importance to this report's purpose so will not be discussed in any greater detail, but may be mentioned throughout the report.

2.3 Current Status

As of April 2008, the JC2Sat Mission is entering the flat-sat testing stage. A flat-sat is a procedure in which all the components are laid out on a table in a clean room, connected one by one, and tested for functionality, first one by one, then for the entire network of components (hence the term flat-sat for a flat table satellite instead of an structurally assembled one).

The mission has passed a Preliminary Design review (in September 2006) in which all aspects of the mission were planned out and analyzed. The mission has also just recently (March 2008) passed a Critical Design Review, which is generally a more in depth and up-to-date version of the Preliminary Design Review. The next step after the flat-sat testing is the complete Mission Readiness Review scheduled for September 2008. The launch itself is targeted for the start of 2010 and the mission will be live through to the start of 2011.

The task taken on by the project's current student was to use a self-made tool to analyze the mission's power situation.

3.0 ANALYSIS USING THE SIMULINK POWER TOOL

This section starts off by briefly explaining the software used on the mission to model such things as Mission Analysis, Software Architecture, and the topic at hand; the Power Budget Tool. One can then understand the larger picture by making connections between the subsystem design, how much power each subsystem uses up, and at what times it uses it.

3.1 MATLAB / Simulink Visual Programming

There is a variety of software tools that the JC2Sat team uses in assisting them to model different aspects of the mission, but the major software language in use is MATLAB. "MATLAB is a high-level language and interactive environment that enables you to perform computationally intensive tasks faster than with traditional programming languages." [9] Within MATLAB, there is a visual programming tool called Simulink. Simulink provides an interactive graphical environment and a customizable set of block libraries that let you design, simulate, implement, and test a variety of time-varying systems [10]. Simulink's operators and tools are all blocks and systems, meaning that they show up as circles, triangles, or most likely rectangles, with icons usually in the middle to represent the operation being done. Another cornerstone of this software is the functionality of subsystems, which allow the user to select a group of blocks, signals, wires, and anything else and group them all together in one box. The box is then called a separate subsystem and can be looked at upon opening it.

This is a very useful tool to have because it allows a functioning program to be easily understandable by other people in the team. This way, knowing how to use the program is not a requirement for being able to read the source. A perfect example of this is the layout of the entire JC2Sat architecture seen in Appendix III, Figure 1 (All the Simulink Print Screens have been organized together in Appendix III along with a List of Appendix Figures, for ease of reference and so as not interfere with the report body).

In this layout the design is kept very simple for something so complex; the entire satellite is split up into payload and communications. At the top level, all viewers can see what major components on the satellite are connected to other major components on the satellite. All the connecting lines represent software connections in this case, where the certain components need to speak with each other. If one needs to see more details, they simply need to go down a layer by double clicking on the desired block / component to see what it is made up of. This way, the source writer can hide complex calculations and algorithms that don't need to be seen from a top level perspective, further down in the program.

The same strategy was maintained when creating the power management tool. After working out calculations, and routing together all the right blocks, the details were layered down into subsystems of Simulink, while the top-level blocks such as user inputs, given universal constants, and final results were brought up to the main level for end users to see. A top level layout of the Power Budget Tool in Simulink can be found in Appendix III Figure 2. The figure demonstrates the simplicity of the program from an end user and manager's perspective. Calculations and details are layered, while inputs (shown in green) are raised to the top level and enlarged. Likewise outputs (blue and orange blocks) are shifted to the right, and enlarged.

Having briefly explained to the reader the basics of Simulink, and the layered design of subsystems, the report can go on to describe the use of the tool itself, within Simulink.

3.2 Graphical User Interface and Inputs

The Power Budget Tool on the JC2Sat project is one that was designed for mission leads to analyze power cases. The Simulink program along with all of the calculations within it, were created by the team's co-op student. This is why it is crucial for the program's Graphical User

Interface (Hereinafter referred to as the GUI) to be easy to use and coincide with all the possible mission scenarios (which will be discussed in the next section).

In order to make the GUI easy to use, it was first separated into 4 different user inputs fields, as seen in Appendix III Figure 2. The four user input categories (Constants, Power Inputs, Scenarios, and Solar Arrays) are seen to the left hand side of the simulation in a pale green colour, and are the first things that should be entered. The following figures are presented for a look at what the interface of each input category looks like. The order which they are entered and applied is irrelevant to the simulation's calculations.

Upon double clicking on the Solar Array inputs, a GUI pops up for the user to input the number of Solar Cells on each side. The sides are defined with the use of a diagram placed within the simulation's main block so that it is visible most of the time. Appendix III Figure 3 shows the Solar Array Inputs GUI.

The reason that the number of solar arrays on each side is a variable is because with a working project this is most likely to change. The purpose of the mission analysis tool was to determine whether there will be sufficient power for the satellite's subsystems throughout different orientations and scenarios. If there is not enough power, there needs to be recommendations for changing the amount of solar cells in order to generate more power. When changed, an iterative process would take place and the new number of cells would be put to the test to see if this change will provide the needed amount of power. The number of cells may change for other reasons as well; such as surface area rearrangement to accommodate for other components. In either case, the number of cells on each side is best made into a user defined variable.

The next set of user inputs are the Mission Scenario Inputs. Similarly the GUI for this block can be brought up by double clicking on it. This GUI looks like the previous one, except it differs in the way that the variables are entered; pop-up menus rather than direct entry edit fields. The choice of pop-up menus was made over edit fields for two reasons; to prevent misspellings of words, and because there is only a finite number of possible scenarios that are being tested. Appendix III, Figure 4 shows the Mission Scenario input screen that appears for the user.

Another set of parameters that the user needs to input are the Power Consumption numbers. The consumption represents three vectors; standby power, operating power, and duty cycle. Each of these 3 then has 16 elements to it which represent the satellite subsystem components that consume power. Table 1 shows the latest component chart data. Note that the full length description of all the acronyms in the Table 1 (as well for all other acronyms within the report) has been given in Appendix I.

Table 1: Latest Component Consumption

Component	Standby Power [Watts]	Operational Power [Watts]	Duty Cycle [%]
SCU	0.3	0.3	100 %
TPCU	0	0.5	70 %
STX	0.05	7	10 %
URX	0.03	0.03	100 %
PDU	0.2	0.2	100 %
ECU	0.165	0.325	100 %
MSS1	0.025	0.06	100 %
MSS2	0.025	0.06	100 %
TAM	0.5	0.5	100 %
TCE	0.05	1.2	50 %
MW1	0.1 (low speed)	0.4 (high speed)	60 %
MW2	0.1 (low speed)	0.4 (high speed)	60 %
GPSR	0	1.6	100 %
GPSA	0.05	0.05	100 %
UTRX	0.05	17	20 %
MIRAD	0	1.3	100 %

The Power inputs try and gather all the same data as Table 1 above, in a format that will allow continuous changes as the project goes on. The user can double click to edit the Standby Power, the Operating Power, or the Duty Cycle. Upon choosing which one of these needs to be changed, edit fields come up for all 16 components, and one can then change each element. Appendix III Figure 5 gives a snapshot of what the Power screen fields.

The simulation has an in-program table that resembles Table 1. Every time the program is run this table is automatically updated, and new numbers are displayed if any changes have been made. The table to the right of the GUI input fields is there for display purposes; to ensure that users can see the latest values for all the components, and so that the most recent table can be extracted into other programs, or printed.

As the name may suggest, the last set of inputs will most likely not be changing over time. They are still displayed within the model for two reasons. First, the constants are there at the top level so that an onlooker can see exactly what initial conditions are going into the model in the case they need to verify the calculations. Secondly, there is the possibility that these constants will change; some less likely than others. For example, the Solar Radiation emitted by the sun's rays per meter squared is something that will be not change during the course of the mission. Meanwhile, initial battery charge is a lot more likely to change because that is a choice on the part of the mission leads. The major difference between the ways these inputs are entered is that there is no GUI. They are changed by double clicking on the Simulink functions themselves and entering the new values. Appendix III, Figure 6 shows all the different constants that need to be entered along with a brief explanation to the side of each one.

In order to create all of the GUI's and their user input variables, a function of Simulink called the Mask Editor was used. The Mask Editor puts a cover over to underlying subsystem, so that when it was clicked on, a GUI would come up rather than just further levels of blocks. Though there were many more, the capabilities of this function that were used included documentation, pop-up parameters, edit parameters, and dialog callbacks. Appendix III, Figure 7 shows how the Mask Editor was used to create the GUIs.

Dialog callbacks (near the bottom of the Mask Editor) were needed in order to not allow certain combinations of pop-ups within the Mission Scenario Inputs. The callbacks needed to be typed in MATAB code and functions because they could not be created with the ease of Simulink visual programming. The full length dialog callback source code that was used to determine whether certain mission scenarios were possible or not is presented in Appendix II. The whole purpose of this was to make things easier for the user, and avoid mistakes.

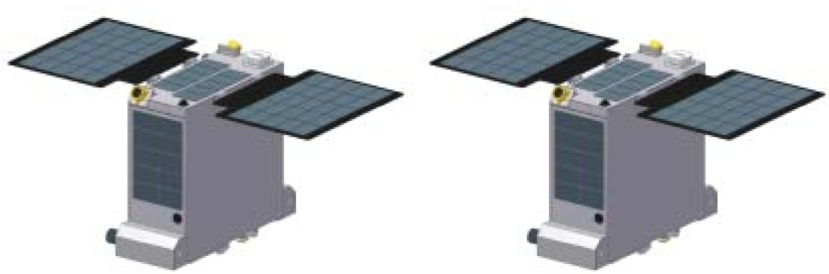
The mistakes to be avoided and the mission scenarios that are not possible are presented in the next section which will first introduce the reader to satellite configurations, and then explain which go on to give all the possible scenarios that could happen to the satellite in orbit.

3.3 Mission Scenarios

There are three configurations that the satellite could be in; Stack, Individual Undeployed, and Individual Deployed. Figure 8 gives pictures of all three configurations.

a) Stack

b) Individual Undeployed



c) Individual Deployed

Figure 2: Satellite Configurations

After the satellites separate from the launch rocket, they are first in the Stack configuration (Figure 8a). They then separate from each other and are in the Individual Undeployed configuration (Figure 8b) and finally, after the motion of the two satellites have been stabilized, the drag panels of each of the satellites open up and they are both in the Individual Deployed configuration (Figure 8c). One distinction must be made when looking at the Stack configuration; the two satellites are mirror images of each other. Meaning that there will be a difference between Stack Satellite A configuration, and Stack Satellite B configuration. Therefore, there are now 4 possible configurations.

The next set of possible scenarios entails the satellite Attitude Situation. In referring to astrodynamics, attitude is defined as "The orientation of an aircraft's axes relative to a reference line or plane, such as the horizon" [11]. So in talking about the Attitude situation, the report refers in essence to the movement that the satellite(s) are undergoing. Table 2 below gives a brief description of the attitude situations which were considered to be possible during the mission (situations such as complete and random loss of earth orbit where neglected).

Table 2: Attitude Situations

	Description
Tumbling	The satellites have been release from the launch vehicle and are spinning
Inter-Satellite	The satellites have stopped spinning and are aimed 10° from each other
Earth-Pointing	The satellites are in an earth pointing Sun Synchronous, Low Earth Orbit
30° Canted	One or both of the satellites has been pointed 30° down in order to drop

The third set of scenarios is the Power Consumption Cases. Many of these cases are taken from standard nomenclature for power systems and satellites, while others have been named simply based on what components are functioning. Table 3 gives a visual representation of all the functioning components in each case. For a full list of acronyms refer to Appendix I.

Table 3: Power Consumption Cases

	Keep-Alive	**Passive ACS**	**Active Low ACS**	**Active High ACS**	**Active High ACS / GPSR**	**Active High ACS / AFF**	**Active High ACS / AFF / MIRAD**
SCU	ON	ON	ON	ON	ON	ON	ON
TPCU	ON	ON	ON	ON	ON	ON	ON
STX	ON	ON	ON	ON	ON	ON	ON
URX	ON	ON	ON	ON	ON	ON	ON
PDU	off	ON	ON	ON	ON	ON	ON

ECU	off	ON	ON	ON	ON	ON	ON
MSS1	off	ON	ON	ON	ON	ON	ON
MSS2	off	ON	ON	ON	ON	ON	ON
TAM	off	ON	ON	ON	ON	ON	ON
TCE	off	Off	ON	ON	ON	ON	ON
MW1	off	Off	ON	ON	ON	ON	ON
MW2	off	Off	ON	ON	ON	ON	ON
GPSR	off	Off	off	off	ON	ON	ON
UTRX	off	Off	off	off	off	ON	ON
MIRAD	off	Off	off	off	off	off	ON

Keep in mind that there is no possible case lower than Keep Alive because this case has only the minimum functioning components. It is important to see that each successive power consumption case builds on the previous one; all the same components are on as in the case one to the left, plus a few others.

Putting all of the three independent scenarios together (4 Satellite Configurations, 4 Attitude Situations, and the 7 Power Consumption Case) one can put together a table of all the possible scenarios that can happen [4x4x7=112 total possible cases]. However, certain situations will never occur, and should be eliminated. An example is that either one of the stack configurations will never be in the Earth-Pointing Attitude Situation because they will never have, and similarly the Individual Deployed configuration will never be in Inter-satellite Separation because it would have already separated. So having eliminated all of the impossible combinations, there are 19 real ones left. Note that this is exactly what the source code (mentioned in the previous section and provided in Append II) is trying to do; prevent the user from choosing a combination of configuration, attitude and power that is not possible [19 are possible and 93 are not possible]. Table 4 gives the 19 possible combinations referred to as the Mission Scenarios.

Table 4: Possible Mission Scenarios

#	Critical	Satellite	Attitude Situation	Power Consumption Case
1		Stack-B	Tumbling	Keep Alive
2		Stack-B	Tumbling	Passive ACS
3	**1**	Stack-B	Tumbling	Active Low ACS
4		Stack-B	Inter-Satellite-Separation	Keep Alive
5		Stack-B	Inter-Satellite-Separation	Passive ACS
6	**2**	Stack-B	Inter-Satellite-Separation	Active Low ACS
7	**3**	Stack-A	Tumbling	Keep Alive
8	**4**	Stack-A	Inter-Satellite-Separation	Keep Alive
9		Indiv.Undeployed	Inter-Satellite-Separation	Keep Alive
10		Indiv.Undeployed	Inter-Satellite-Separation	Passive ACS
11		Indiv.Undeployed	Inter-Satellite-Separation	Active Low ACS
12	**5**	Indiv.Undeployed	Inter-Satellite-Separation	Active High ACS
13		Indiv.Undeployed	Earth-Pointing	Active High ACS
14	**6**	Indiv.Undeployed	Earth-Pointing	Active High ACS / GPSR
15		Indiv.Deployed	Earth-Pointing	Active High ACS / GPSR
16		Indiv. Deployed	Earth-Pointing	Active High ACS / AFF
17	**7**	Indiv.Deployed	Earth-Pointing	Active High ACS / AFF / MIRAD
18		Indiv.Deployed	30° Canted	Active High ACS / AFF
19	**8**	Indiv.Deployed	30° Canted	Active High ACS / AFF / MIRAD

The 8 critical scenarios highlighted in Table 4 are the ones that were preliminarily assessed by mission analysis leads and systems engineers to be the most important. They are the most important because it is more likely during these scenarios that the satellite will be nearing a danger zone, in which the battery is highly depleted. The danger may be caused by either high amounts of power consumption (many components are on) and/or a low amount of power generation (solar arrays are not well exposed to sunlight). The next section will describe how power is generated and when it will peak and drop. The Critical Mission Scenarios will be used again later on to generate results, conclusions and recommendations.

4.0 POWER GENERATION

This section explains how the solar arrays convert solar radiation into power for the satellite's subsystems to use or for the battery to store. The section also gets into the details of orbital mechanics of the satellites and the angles at which solar cells will be exposed to the sun at different times of the day.

4.1 Solar Cells

There are several types of power sources that could be used on a satellite. Among them are nuclear energy, chemical energy, solar cells, and non-rechargeable batteries. Solar cells, which convert solar radiation into useable electrical energy, were chosen for this project because they work well with Low Earth Orbits and also with mission times within the range of a few weeks to years. The other energy sources are catered towards shorter or longer missions or for missions further away from the sun where the intensity of its rays has degraded.

Solar cells typically have an efficiency of about 14-25% (although experimentally, much higher and lower efficiencies exist); meaning that only that percentage of the solar radiation can be converted to useable electrical energy [12]. The lower end of that range is made up of single junction solar cells such as standard silicon cells. The upper, and more desired, end of the range comes from multiple junction solar cells, such as the triple junction GaAs Solar Cells that are being used on this project. The efficiency of these cells is typically up to 25% in lab testing, and is considered approximately 23% in real mission uses, so this will be the efficiency used from here on. The multi-junction solar cells present an advantage over single junction ones by having multiple layers semiconductor layers with different band gaps. Each of the layers is comprised of a different material (usually a group III-V semiconductor) and absorbs a different portion of the spectrum [12]. If the band gap energy of a material is larger than that of the energy of an incident photon, then the photon does not have enough energy to excite from the conduction band to the valence band. On the other hand, if the incident photon has a higher energy than that of the band gap, the excess energy is given of in the form of heat, and is inefficient at converting solar radiation into electrical energy. The second and third layers in a triple junction solar cell are made up of materials with different band gap energies that can absorb more incident photons that would not have been initially grabbed by the one layer alone. The top layer has the largest band gap, and each successive layer afterwards has a smaller band gap. This way, any photons that do not have enough energy to create an electron-hole pair, pass through the top layer and get a second shot at absorption in the successive layers [12].

Knowing the type of solar cells used and their efficiency, it is now appropriate to move on to a representation of how much sunlight the cells actually receive.

4.2 Calculations

All the calculations for the simulation were based on the foundation of projecting solar array planes as if they were perpendicular to a set of body centered normal vectors. The normal vectors that were used is given in Figure 9 below.

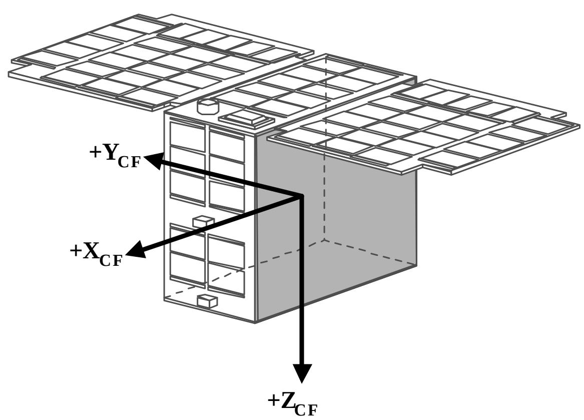


Figure 3: Body Centered Normal Vectors

From this figure one can see how normal vectors are defined in orbital mechanics with a satellite as a central body. The positive 9 direction represents the direction that the satellite is travelling in. The positive y direction represents the normal to the orbital plane of the satellite. The positive z direction represents the Nadir (pointing from the centre of the satellite directly below it).

The next important factor is how this coordinate system was used to obtain a set of power generation calculations. The first and most important power generation formula used is given in equation 1.

$$I_{ind} = A \cdot K \cdot F \quad \text{(equation 1)}$$

Where I_{ind} gives the average solar radiation input on any spacecraft face over an orbit in Watts, and A is the surface area of the plane in meters squared. K is the solar constant in the vicinity of the earth (1367 W/m^2 for all cases on this mission), and F gives the fraction of the surface area projected in the direction of the sun, and it must lie between 1 and 0 (unit less). To get the total average solar radiation of all the face planes, and therefore the entire spacecraft, the sum of all the individual faces just needs to be added up as given in equation 2 [12].

$$I_{tot} = \sum_{1}^{n} I_{ind} \quad \text{(equation 2)}$$

From equation 1, F, the fraction of the projected surface area is the only variable that requires investigation, and a formula to obtain it can be seen in equation 3[12] below.

$$F = \widehat{N} \cdot \hat{S} \quad \text{(equation 3)}$$

Where $\widehat{N}$ is the Normal to the plane in question (refer back to Figure 9), and $\widehat{S}$ is the sun vector given in the satellite body centered reference frame. The dot product between these two vectors will produce a fraction between 0 and 1 that will reduce the usable energy coming from the sun's rays in proportion to how large of an angle there is between the solar panel face and the sun. With the use of the Power Budget tool, a function was put in that would eliminate all angles greater than 90° because it is the back of the solar panel that will be seeing the sun/s rays and will not be able to convert anything to usable energy.

There were also a few other important factors that were included into the raw calculations of power generation, one of which was the Albedo Effect, by which the sun's radiation gets reflected off of the earth's atmosphere and clouds, and gets sent back out into space. This becomes beneficial to the spacecraft's power generation because it can only add to the amount of sunlight the solar arrays are receiving, especially the ones at the bottom of the craft, or potentially underneath the drag panels. A second important factor is the Kelly Cosine Law for Solar Cells, which gives a set of experimental numbers to use in place of real cosine values. The reason the numbers are skewed from set cosine values is because after the incident angle of light is greater than approximately 55°, the conversion of photons becomes imperfect and fades further and further until reaching a cosine value of 0 at approximately 80-85° (where as with the actual cosine law it should reach a zero value at exactly 90°) [12]. Further details of how the Kelly Cosine Law and the Albedo effect were built into the simulation are not of relevance to the purpose of this report, so it is only important to note that the Kelly Cosine Law will produce a slightly negative effect on power generation at increasing angles, and that the Albedo effect will add to the power generation of solar panels placed on the bottom side craft (whose normals are z positive, in Figure 9).

Periods of satellite eclipses were also incorporated in the Power Budget Tool. This function looked at the location of the satellite relative to the earth and sun and determined whether it was in light or darkness and then multiplied the entire power generation by either 1 (if it was in light) or zero (if it was in darkness, because it can't generate anything in eclipse). The difference in umbra and penumbra light intensities has been neglected because the satellite's orbit is fast enough that it will be passing through the intermediate phase too quickly to have any significant effect on the calculations.

Given all the calculations, eclipses, effects and laws that have been built into the power generation block of the Power Budget Tool, the only remaining thing is for the user to choose the scenario which the satellite will be experiencing. Table 5 gives the actions that will be taken as the user takes into account the different satellite configuration cases.

Table 5: Number of Solar Cells per Orientation

	Xpos	Xneg	Ypos	Yneg	Zpos	Zneg
1) Stack (sat A)	SA6	SA4	SA2	0	SA5	SA3
2) Stack (sat B)	SA4	SA6	0	SA2	SA5	SA3
3) Indiv. Undepl.	SA4	SA6	SA1	SA2	SA5	SA3
4) Indiv. Deployed	SA4	SA6	0	0	SA5+SA7+SA8	SA1+SA2+SA3

The difference between the two stack configurations is that they are facing different ways, otherwise they are the same. In the Individual Undeployed case, the sides that were previously blocked by the neighbouring twin satellite are now exposed, and finally in the deployed case the drag panels have been opened and the extra Solar Arrays are exposed (for a reminder of what the configurations look like, refer back to Figure 8, and for a reminder of where each Solar Array / SA is located refer back to Figure 2).

The other relevant part of the scenario is the attitude situation of the satellite given back in Table 2. Depending on this, the normal vectors are shifted by whatever degree the attitude is in (for example in the 30° Canted situation, the normal vectors are shifted forward by 30° and in the Earth Pointing situation, the normal vectors are kept as they are).

5.0 POWER STORAGE

The JC2Sat mission will use two NiCd Batteries, a power regulator and a Power Distribution Unit (PDU) to take in the electrical power converted by the solar cells, and either send it straight to the satellite's components and subsystems for consumption if the battery is fully charged, or if the battery is not full it will store it for later use during periods when it is needed the most (eclipses).

As discussed in the user inputs section, the user can set the initial battery charge value to whatever that may be when the mission is set to launch. The maximum battery value also may be changed, but it is most likely to stay constant at its current level of 32.3 Whr. This value will help to determine the depth of discharge, a crucial criteria in the analysis of the initial problem of whether there will be enough power during the mission scenarios.

5.1 Calculations

The battery function that was built in to the Power Budget Tool in Simulink was simpler than the power generation tool because it involved only one algorithm. This algorithm compared the generation and consumption powers as well as current battery levels (which were stored in a memory function. If the battery was full and more power was being generated then consumed, the battery was left out completely and the excess power was not used. In all other cases (battery was full and consumption exceeded generation, or if the battery was not full) the action could be represented by equation 4 [12] below.

$$Batt_N = Batt_O + P_{Gen} - P_{Cons} \quad \text{(equation 4)}$$

In which $Batt_N$ represents the New Battery Level, $Batt_O$ represents the Old Battery Level, P_{Gen} represents the Power Generated, and P_{Cons} represents the Power Consumed.

Another quick calculation is the derivation of the previously given maximum battery value of the 32.3 Whr. This comes from applying a coefficient of 0.95 (95%) to the theoretical maximum battery value of 34 Whr. The coefficient comes from taking into account differences between beginning of life and end of life efficiencies of the battery. Since all batteries degrade over time, and with every successive use not being perfect as the one before, and due to memory effects, the NiCd batteries will degrade up to 5% over the course of a yearlong mission [12]. Rather than putting in complicated calculations that would take into account battery degradation as a function of time, the model assumed a worst case scenario and took the end of life value to be constant throughout the whole mission. The worst case scenarios are used constantly throughout the Power Budget Tool because there may be extra things in real life that can go wrong, and it is always better to plan for the worst.

Given these few simple calculations, the battery level can now be further assessed to obtain a depth of discharge.

5.2 Depth of Discharge

The Depth of Discharge of a battery is a universally used method for determining current battery levels. Equation 5 [12] gives the formula for determining Depth of Discharge.

$$DOD = \frac{Batt(t)}{Batt_{Max}} \qquad \text{(equation 5)}$$

In this equation Batt(t) represents the current battery level as a function of time, $Batt_{Max}$ is the maximum battery charge value as given earlier to be 32.3 Whr (or whatever this value may change to if the user inputs something else), and DOD represents the Depth of Discharge. An observation to make is that this value represents the inverse of commercially popularized battery levels which are given in percentage of full battery values (i.e. a full battery in terms of DOD is 0% and in terms of commercial products such as cellular phones is 100%).

One of the main purposes of this report is to make sure that Depth of Discharge levels do not exceed recommended industry maximum values, which for short duration spacecraft missions of a year or less are at approximately 25-30% Depth of Discharge [12]. This report will use a threshold value of 25%, so that if the DOD level reaches a point of 25% or greater during the mission, extra cells will need to be added to compensate for the power consumption.

6.0 POWER CONSUMPTION

The power consumption of the JC2Sat mission was modeled together with the generation and storage within the Power Budget Tool. The majority of the work was done on the user's part by entering in the chart of values.

6.1 Calculations

From the most recently saved chart of consumption values entered by the user, the Standby Power, Operating Power and Duty Cycle are separated into vector form. Then the use of equation 6 is employed.

$$P_{Cons\ Ind} = P_{Op} \cdot Duty\ Cycle \qquad \text{(equation 6)}$$

Here, $P_{Cons\ Ind}$ represents the power consumption of an individual component, and P_{Op} is the operating power of that same individual component. There were only a few cases in which the standby power needed to be used (Momentum Wheels 1 and 2) and then the operating power was replaced with the standby power in equation 6. Once all the individual component wattages had been obtained, they were all summed up with the use of equation 7 below.

$$P_{Cons\ Tot} = \sum_{1}^{n} P_{Cons\ Ind} \qquad \text{(equation 7)}$$

Where $P_{Cons\ Tot}$ represents the total power consumption of all the components. This value varies with the Power Case chosen as seen back in Table 3. The Keep Alive Case produces the smallest $P_{Cons\ Tot}$ and each successive case produces larger and larger numbers because they consume more and more power.

6.2 Averaging

The average power consumption over the orbit was used rather than specific time dependent peaks for two reasons. First the time it takes for the satellite to orbit once around the earth (approximately an hour and a half) is so short that full maneuvers and scenario changes will take longer to perform than a single orbit, and second the average will produce nearly identical results to the time dependent power consumption because the majority of the components are either on or off (100% duty cycle) so the numbers for these would be identical to averaging. There are a few components that operate during certain parts of the orbit, such as relaying communications information using the antennas and receivers when the satellite is over top of ground communication stations in Japan or Canada.

Having looked at the created Power Budget Tool for analyzing the initial problem and the process that the tool goes through to analyze the different scenarios, the reader is prepared to see the results of the report.

7.0 RESULTS

The results obtained from the engineering analysis are presented in the form of graphs generated by running simulations in the Simulink Power Budget Tool. The graphs give the three most vital characteristics of the satellite's power situation; how much is being generated, how much is being consumed, and the depletion of discharge, all as a function of time.

7.1 Graphs Produced

The graphs are presented on the same axis because this gives the best overall view of what is going on. For all three lines, the x-axis represents simulation time and therefore real life time in seconds as well. The y-axis represents Power (generated or consumed) in Watts and for the Depletion of Discharge line it represents the depletion of discharge as a percentage (%). On all graphs power generation is given in yellow, power consumption is given in cyan, and the depth of discharge is given in magenta.

Three of the Critical Scenarios from Table 3 are presented; scenarios 2, 6, and 8. Only these scenarios were chosen to be displayed because the other half represents a nearly identical set of scenarios with the only difference being a lower power mode (treating Stack A and Stack B as nearly identical). A scenario with the same configuration and attitude situation, but a lower power mode will always be in a better power situation than the same scenario with a higher power mode. The worse case scenarios were used for the results. Figure 4 shows the results of the simulation on Critical Scenario 2 (Stack B, Inter-Satellite Separation, Low Active ACS).

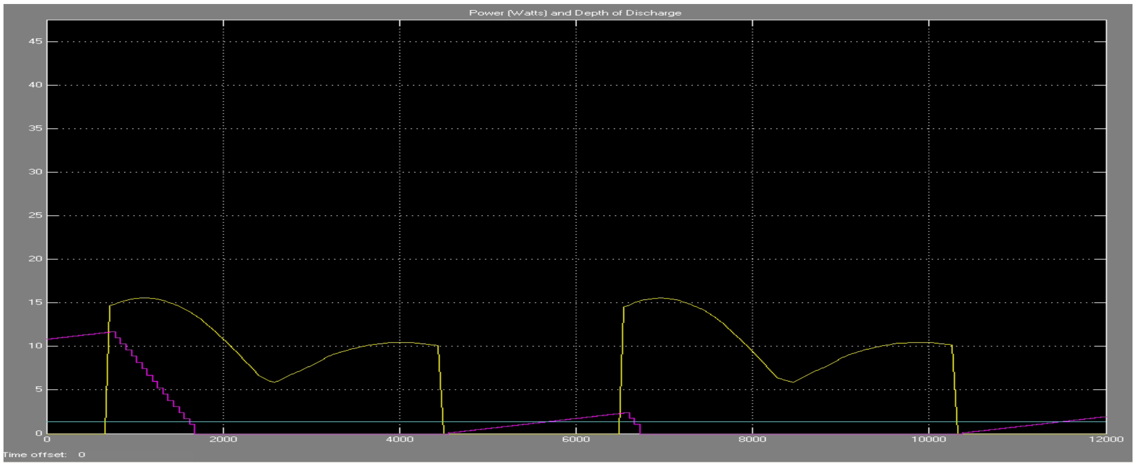


Figure 4: Critical Scenario 2

This figure shows that in the stack configuration there isn't much power being generated, but there also isn't very much power being consumed because power hogging communications operations aren't being performed and neither are other high power functions (GPS, MIRAD etc.). As a result the battery does not run out, and after the first spike (because the battery doesn't start fully charged) it doesn't go anywhere near the 25% depletion of discharge that has been set as a criterion that would signal need for change.

Figure 5 then shows Critical Scenario 6 (Individual Undeployed, Earth Pointing, High Active ACS / GPSR).

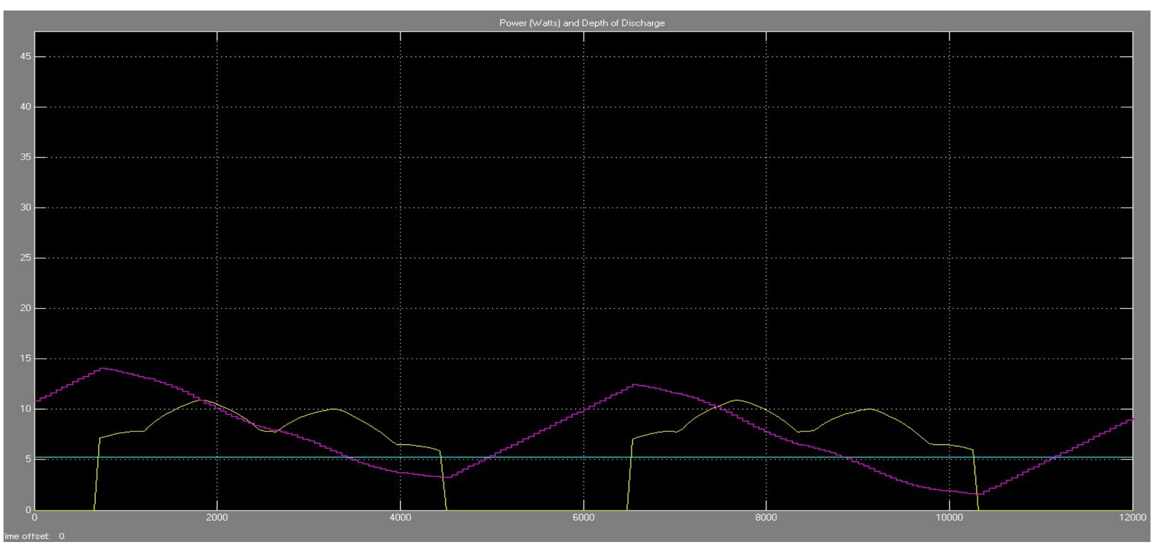


Figure 5: Critical Scenario 6

Similar results come up for this figure, in which the largest area of solar cells, the drag panels, have not yet been deployed, so the satellite can not yet generate very much power. At the same time the mission has not yet started its major objectives so it does not consume much power. As a result the battery does not run out and the DOD does not reach 25%.

Figure 6 shows the simulation graph for Critical Scenario 8 (Individual Deployed, 30° Canted, Active High ACS / AF / MIRAD)

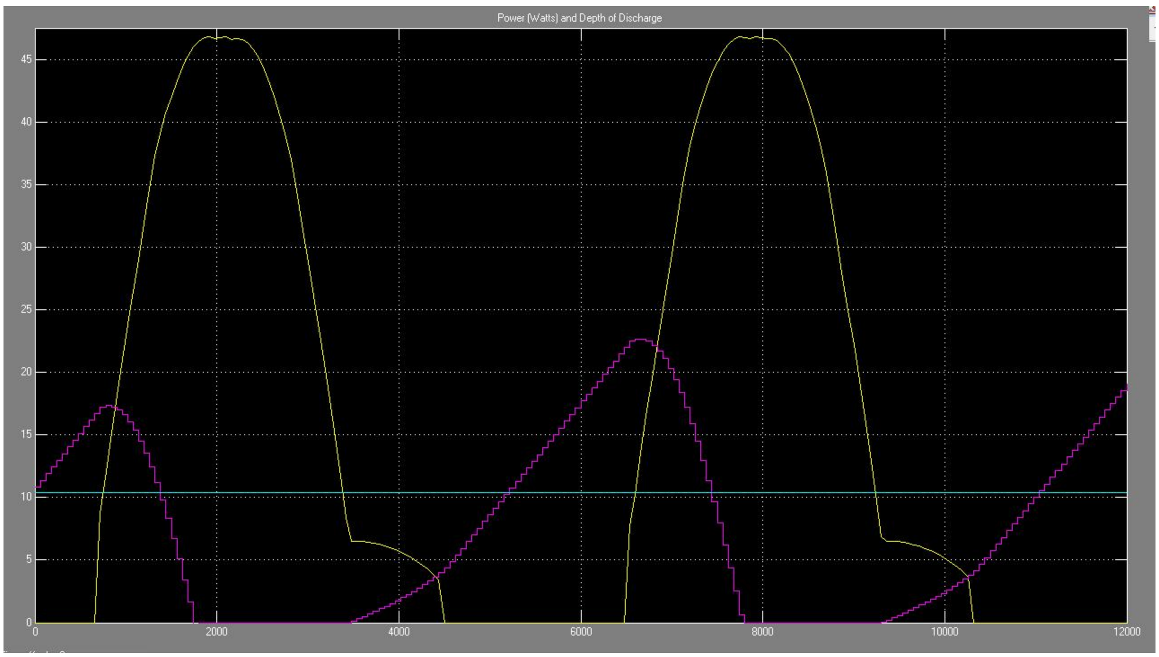


Figure 6: Critical Scenario 8

This figure shows a much more common case during the mission; deployed panels. The differences are obvious at first glance. There are large power generation spikes and drops corresponding to optimal sun angles and eclipses, respectively. Here the mission is in full swing and power is being consumed at its highest case during the entire mission, and still the battery does not run out and stays clear of the 25% DOD threshold, although it does near it.

Figure 7 shows Critical Scenario 8 once again for comparison purposes, but this with an additional 18 solar cells on the bottom of each drag panel.

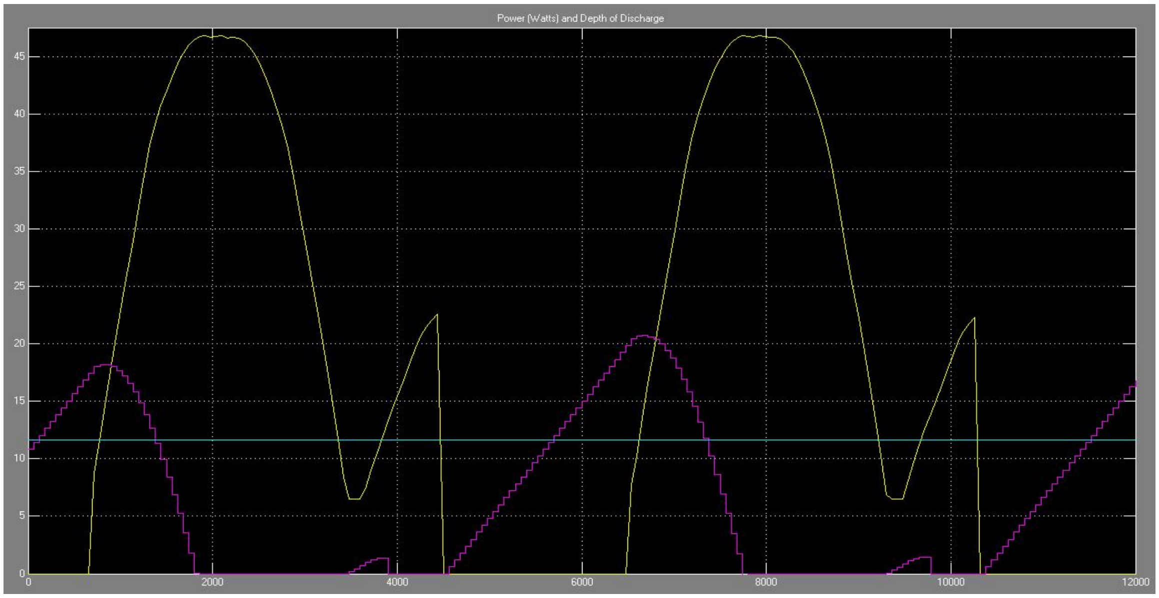


Figure 7: Critical Scenario 8 with Extra Solar Cells

The number of solar cells at the bottom was chosen by the project lead as a preliminary example to investigate the benefit of a few extra strings of cells. The exact number itself can be tempered with in future cases, but for the time being a medium amount of cells was chosen making sure that they would fit under the drag panels. It can be seen here that when the craft turns sideways (at the bottom of the large peaks) instead of dropping off slowly, there is a minor peak created that will supply extra power at a perfect time; right before eclipse.

Using the results of the worst case critical scenarios, the report can now be summarized.

8.0 SUMMARY

This section talks about the implications that the results have on answering the problem at hand, and the recommendations that should be carried through with in the future.

8.1 Conclusions

It is concluded that the battery will not run out or exceed a 25% depletion of discharge, and that extra solar cells beneath the satellite would be beneficial.

The first major conclusion drawn from the graphs is that the satellite's battery will not fully deplete at any point in the mission. The worst case critical scenario results showed that even though there were times when the power consumption of the satellite exceeded the power generation, the battery still had enough stored charge to supply the satellite with the power that it required. The battery never ran out, and the mission was able to carry out all its objectives without difficulties.

The second major conclusion that is drawn upon from the results is that the satellite's battery does not reach a depth of discharge higher than the industry recommended maximum value. The results showed that the depth of discharge was never above 25%, even during eclipses and when the satellite's panels were not fully deployed. So the conclusion is that spacecraft suggested battery levels have been maintained, and the criterion of has been met.

The final conclusion is that additional solar cells on the bottom of the satellite's drag panels would be beneficial. Results show that when extra cells were added to the bottom of drag panels the satellite generated extra power peaks when turned sideways just prior to eclipse.

8.2 Recommendations

From the conclusions in the previous section, the report can draw upon recommended courses of action for future resource allocation on this mission.

The first major recommendation is that a satellite structural bus and payload redesign should not take place. The conclusions showed sufficient power for survival in critical test cases and there should be no resources allocated towards rearranging components and subsystems.

The second recommendation is that it is not crucial to add extra GaAs solar cells if there isn't enough room to accommodate them. The conclusions showed that it is not necessary, but is beneficial to add cells. So it is recommended to allocate time and resources towards investigating the placement of solar strings underneath each drag panel.

The third and final recommendation of this report is that the Simulink Power Budget Tool should be used in the future for the production of more charts showing the benefit of specific numbers of solar cells, if it is within the mission's financial constraints. The tool was very useful in produces visual results and should be put into further action by entering anywhere from zero to as many solar cells that can fit on the bottom of the drag panels or anywhere else that the team finds to be suiting.

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APPENDIX I – ACRONYMS

ACS	Attitude Control Subsystem
ACM	Acquisition Mode
ACS	Attitude (and Orbit) Control System (used for 3-letter code system)
ACSF	Attitude (and orbit determination and) Control Flight Software
AD	Applicable Document
ADC	Analog-to-Digital Converter
ADM	Attitude Determination Method
AFC	Autonomous Formation Control
AFF	Autonomous Formation Flight
ANTC	AntCom
AOCS	Attitude and Orbit Control Subsystem
AR	Acceptance Review
BAT	Battery Assembly
BBM	Bread-Board Model
BGA	Ball Grid Array
CAD	Canadian Dollar
CANX	Canadian Advanced Nanospace eXperiment
CCR	Corner Cube Reflector
CDH	Command and Data Handling
CDR	Critical Design Review
CL	Current Limit
CMS	Component Management Sheet
CoCom	Coordinating Committee for Multilateral Export Controls
COM	Communications subsystem
COSS	Component Specification Sheet (was "CSS" but changed due to conflict with other CSS)
COTS	Commercial Off-The-Shelf
CP	Circular Polarization
CSA	Canadian Space Agency
CSR	Conceptual Study Review
CSS	Coarse Sun Sensor
CTM	Core Team Meeting
CVCM	Collected Volatile Condensable Material
CVT	Constant Voltage Transformer
CW	Counter Weight
CW	Clohessy Wiltshire
D/L	Downlink
DB	Database
DDP	Differential Drag Panel
DoD	Death of Discharge
DP	Drag Panel
DS	Dynacon
DSF	Design Safety Factor
DTM	Detumbling Mode
ECEF	Earth Centered Earth Fixed
ECU	Extended Control Unit
EDB	ECU Daughter Board
EIRP	Effective Isotropic Radiated Power
EKF	Extended Kalman Filter
ELK	Elkel
EM	Engineering Model
EMC	Electro-Magnetic Compatibility

EMF	Earth Magnetic Field
EMI	Electro-Magnetic Interference
EPM	Earth Pointing Mode
EPS	Electrical Power Subsystem
ESD	Electrical System Diagram
ESD	Electro-Static Discharge
FDIR	Fault Detection Isolation and Recovery
FDMA	Frequency Division Multiple Access
FEA	Finite Element Analysis
FEC	Forward Error Control
FF	Formation Flying/Flight
FIR	Far Infra-Red
FLS	Flatsat
FM	Formation Maneuvering
FRR	Flight Readiness Review
FSN	Fasteners
FTM	Full Team Meeting
G/S	Ground Station
GaAs	Gallium Arsenide (solar cells)
GBRN	GPS-Based Relative Navigation
GMSK	Gaussian Minimum Shift Keying
GN&C	Guidance Navigation & Control
GPS	Global Positioning System
GPSA	GPS Antenna
GPSR	GPS Receiver
GS	Ground Segment
H/W	Hardware
H2A	(JAXA Launcher)
HK	House Keeping
HPOP	High Precision Orbit Propagator
HRM	Hold and Release Mechanism
I&T	Integration & Test
I/F	Interface
I/O	Input Output
IAT	(JAXA) Institute of Aerospace Technology
ICD	Interface Control Document
IFC	(Main Computer)
IFOV	Instantaneous Field-Of-View
IGRF	International Geomagnetic Reference Field
IGS	International GPS Service
IINS	Integrated Inertial Navigation System
IMU	Inertia navigation Measurement Unit
INO	National Optics Institute (Institut national d'optique)
INS	Inertial Navigation System
IR	InfraRed
ISM	Inter-satellite Separation Mechanism
ISRR	Inter-satellite Separation Readiness Review
JAXA	Japan Aerospace Exploration Agency
JC2Sat	Japan Canada Joint Collaboration Satellite
JC2Sat-FF	Japan Canada Joint Collaboration Satellite - Formation Flying
JCF	Japan Canada Joint Collaboration Satellite - Formation Flying
K/O	Kickoff
LC	Inductor and Capacitor
LEO	Low Earth Orbit
LNA	Low Noise Amplifier
LRA	Laser Reflector Assembly

LRR	Launch Readiness Review
LSM	Launch Vehicle Separation Mechanism
LTDN	Local Time of Descending Node
LV	Launch Vehicle
LVLH	Local Vertical Local Horizontal
LWIR	Long-Wave InfraRed
MDD	Mission Definition Document
MHS	Micro Horizon Sensor
MIR	MIRAD
MIRAD	Miniature far Infrared RADiometer
MOU	Memorandum of Understanding
MRD	Mission Requirements Document
MSS	Medium Sun Sensor
MTM	Mechanical Test Model
MTQ	Magnetic Torquer
MW	Momentum Wheel
NASA	National Aeronautics and Space Administration
NC	Non-Conformance
NETD	Noise Equivalent Temperature Difference
NiCd	Nickel Cadmium (batteries)
NRE	Non-Recurring Engineering (cost)
NV	NovAtel
OBC	On-Board Computer
OBS	On-Board Software
ODM	Orbit Determination Method
OEM	(GPS Receiver)
OLR	Outgoing Longwave Radiation
OR	Oscillation Reduction
ORR	Operational Readiness Review
OS	Operating System
OVP	Over Voltage Protection
PDM	Panel Deployment Mechanism
PDR	Preliminary Design Review
PDU	Power Distribution Unit
PFD	Power Flux Density
PFM	Proto-Flight Model
PIR	Pre-Integration Review
PM	Prototype Model
PM	Position Maintenance
PRR	Preliminary Requirements Review
QR	Qualification Review
R&D	Research and Development
RC	Rotor Controller
RD	Reference Document
RF	Radio Frequency
RFP	Request For Proposal
RHCP	Right Hand Circular Polarization
RNS	Relative Navigation System
ROIC	ReadOut Integrated Circuit
RPDM	Relative Position Determination Method
RSS	Root Sum Square
RU	Ryerson University
S/C	Spacecraft
S/W	Software
SACM	Stack Acquisition Mode
SANT	S-band Antenna

SAP	Solar Array Panel
SAR	System Acceptance Review
SC	Solar Cells
SCPL	S-band Coupler
SCU	Satellite Control Unit
SDPX	S-band Duplexer
SDR	System Definition Review
SDS	Small Demonstration Satellite (JAXA)
SE	Systems Engineer
SEE	Single Event Effect
SEL	Single Event Latch-up
SEU	Single Event Upset
SFL	Space Flight Laboratory (UTIAS)
SHM	Save Hold Mode
SIM	AOCS Simulation
SINT	Sinclair Interplanetary
SLR	Satellite Laser Ranging
SMA	S-band Multiple Access
SMS	Structures and Mechanisms Subsystem
SOE	Sequence Of Event
SOP	System Operations Procedures
SPI	Serial Peripheral Interface
SQ	SpaceQuest
SRFS	S-band RF Switch
SRR	System Requirements Review
SRX	S-band Receiver
SSP	Simple Serial Protocol
SSTL	Surrey Satellite Technology Inc
STB	Space Technologies Branch
STBY	Standby Mode
Std. Dev.	Standard Deviation
STDP	Space Technology Development Program
STDRC	Space Technology Demonstration Research Center
STK	Satellite Tool Kit
STM	Structural Thermal Model
STR	Structure
STRP	Space Technology Research Program
STX	S-band Transmitter
SWIR	Short Wavelength InfraRed
SYS	System
TAM	Three-Axis Magnetometer
TBC	To Be Confirmed
TBD	To Be Determined
TPCU	Thermal & Power Control Unit
TBR	To Be Revised
TBW	To Be Written
TC	Telecommand
TCE	Torquer Control Electronics
TCS	Thermal Control Subsystem
TDMA	Time Division Multiple Access
TEC	ThermoElectric Cooler
TLE	Two-Line Element
TLM	Telemetry
TM	Telemetry
TML	Total Mass Loss
TNC	Thermal Node Controller

TNR	Test Non-conformance Report
TPCU	Telemetry and Power Control Unit
TRIAD	Name of a well known attitude determination method. The meaning is TRI = three axis, A = attitude, D = determination
TRL	Technology Readiness Level
TS	Temperature Sensor
TT&C	Telemetry, Tracking and Command
TVAC	Thermal Vacuum
U/L	Uplink
UANT	UHF Antenna
UCPL	UHF Coupler
UFIL	UHF Filter
UHF	Ultra High Frequency
UPS	Uninterruptible Power Supply
URX	UHF Receiver
UTIAS	University of Toronto Institute of Aerospace Studies
UTRX	UHF Transceiver
UTX	UHF Transmitter
VANT	VHF Antenna
VDM	VHF antenna Deployment Mechanism
VFIL	VHF Filter
VHF	Very High Frequency
VTRX	VHF Transceiver
w/o	Without
WBS	Work Breakdown Structure
WGS	World Geodetic System

APPENDIX II – SOURCE CODE FOR DIALOG CALLBACKS

```
% Define Variables: c=configuration, a=attitude, p=power

c= get_param('propagator_HF/Plant/System Equations/Orbit propagation
master/satellite dynamics/SRP/Solar Panel Power Generation Tool/Power
Management/Scenarios','Config');

a= get_param('propagator_HF/Plant/System Equations/Orbit propagation
master/satellite dynamics/SRP/Solar Panel Power Generation Tool/Power
Management/Scenarios','Att');

p= get_param('propagator_HF/Plant/System Equations/Orbit propagation
master/satellite dynamics/SRP/Solar Panel Power Generation Tool/Power
Management/Scenarios','Pow');


% When Satellite A is in stack configuration select Keep Alive
automatically and allow
% This line of code is only in the Config Dialog Callback box because
it is the one being selected as Stack A

if strcmp(c(12),'A')
    set_param('propagator_HF/Plant/System Equations/Orbit propagation
master/satellite dynamics/SRP/Solar Panel Power Generation Tool/Power
Management/Scenarios','Pow','Keep Alive')
    set_param('propagator_HF/Plant/System Equations/Orbit propagation
master/satellite dynamics/SRP/Solar Panel Power Generation Tool/Power
Management/Scenarios','MaskEnables',{'on','on','on'})
else
    set_param('propagator_HF/Plant/System Equations/Orbit propagation
master/satellite dynamics/SRP/Solar Panel Power Generation Tool/Power
Management/Scenarios','MaskEnables',{'on','on','on'})
end


% STACK A CONFIGURATIONS
% Alert user if Stack A is combined with an Attitude of Earth Pointing
or 30deg Canted

if and(strcmp(c(12),'A'),or(strcmp(a(1),'E'),strcmp(a(1),'3')))
    error('An Invalid Scenario Possibility has been entered, please try
again.')
end


% STACK B CONFIGURATIONS
% Alert user if Stack B is combined with an Attitude of Earth Pointing
or 30deg Canted

if and(strcmp(c(12),'B'),or(strcmp(a(1),'E'),strcmp(a(1),'3')))
    error('An Invalid Scenario Possibility has been entered, please try
again.')
end

% Alert user if Stack B is combined with any Power Case with High ACS
```

```
if and(strcmp(c(12),'B'),strcmp(p(8),'H'))
    error('An Invalid Scenario Possibility has been entered. Please try again.')
end


% INDIVIDUAL UNDEPLOYED CONFIGURATIONS
% Alert user if Individual Undeployed is combined with an Attitude of Tumbling or 30deg Canted

if and(strcmp(c(12),'U'),or(strcmp(a(1),'T'),strcmp(a(1),'3')))
    error('An Invalid Scenario Possibility has been entered. Please try again.')
end

% Alert user if Individual Undeployed is combined with an Attitude of Inter-Satellite Separation and a Power Case of Active High ACS / GPS or higher

if strcmp(c(12),'U') & strcmp(a(1),'I') & strcmp(p(17),'/')
    error('An Invalid Scenario Possibility has been entered. Please try again.')
end

% Alert user if Individual Undeployed is combined with an Attitude of Earth Pointing and a Power Case of Active High ACS / AFF or higher

if strcmp(c(12),'U') & strcmp(a(1),'E') & strcmp(p(19),'A')
    error('An Invalid Scenario Possibility has been entered. Please try again.')
end

% Alert user if Individual Undeployed is combined with an Attitude of Earth Pointing and a Power Case of Keep Alive or Passive ACS

if strcmp(c(12),'U') & strcmp(a(1),'E') &
or(strcmp(p(1),'K'),strcmp(p(1),'P'))
    error('An Invalid Scenario Possibility has been entered. Please try again.')
end

% Alert user if Individual Undeployed is combined with an Attitude of Earth Pointing and a Power Case of Active Low ACS

if strcmp(c(12),'U') & strcmp(a(1),'E') & strcmp(p(8),'L')
    error('An Invalid Scenario Possibility has been entered. Please try again.')
end


% INDIVIDUAL DEPLOYED CONFIGURATIONS
% Alert user if Individual Deployed is combined with an Attitude of Tumbling or Inter-satellite Separation

if and(strcmp(c(12),'D'),or(strcmp(a(1),'T'),strcmp(a(1),'I')))
    error('An Invalid Scenario Possibility has been entered. Please try again.')
end
```

```
% Alert user if Individual Deployed is combined with an Attitude of
Earth Pointing and a Power Case of Active High ACS or lower

if strcmp(c(12),'D') & strcmp(a(1),'E') & ~strcmp(p(17),'/')
    error('An Invalid Scenario Possibility has been entered. Please try
again.')
end

% Alert user if Individual Deployed is combined with an Attitude of
30deg Canted and a Power Case of Active High ACS / GPSR or lower

if strcmp(c(12),'D') & strcmp(a(1),'3') & ~strcmp(p(19),'A')
    error('An Invalid Scenario Possibility has been entered. Please try
again.')
end
```

APPENDIX III – SIMULINK POWER BUDGET TOOL

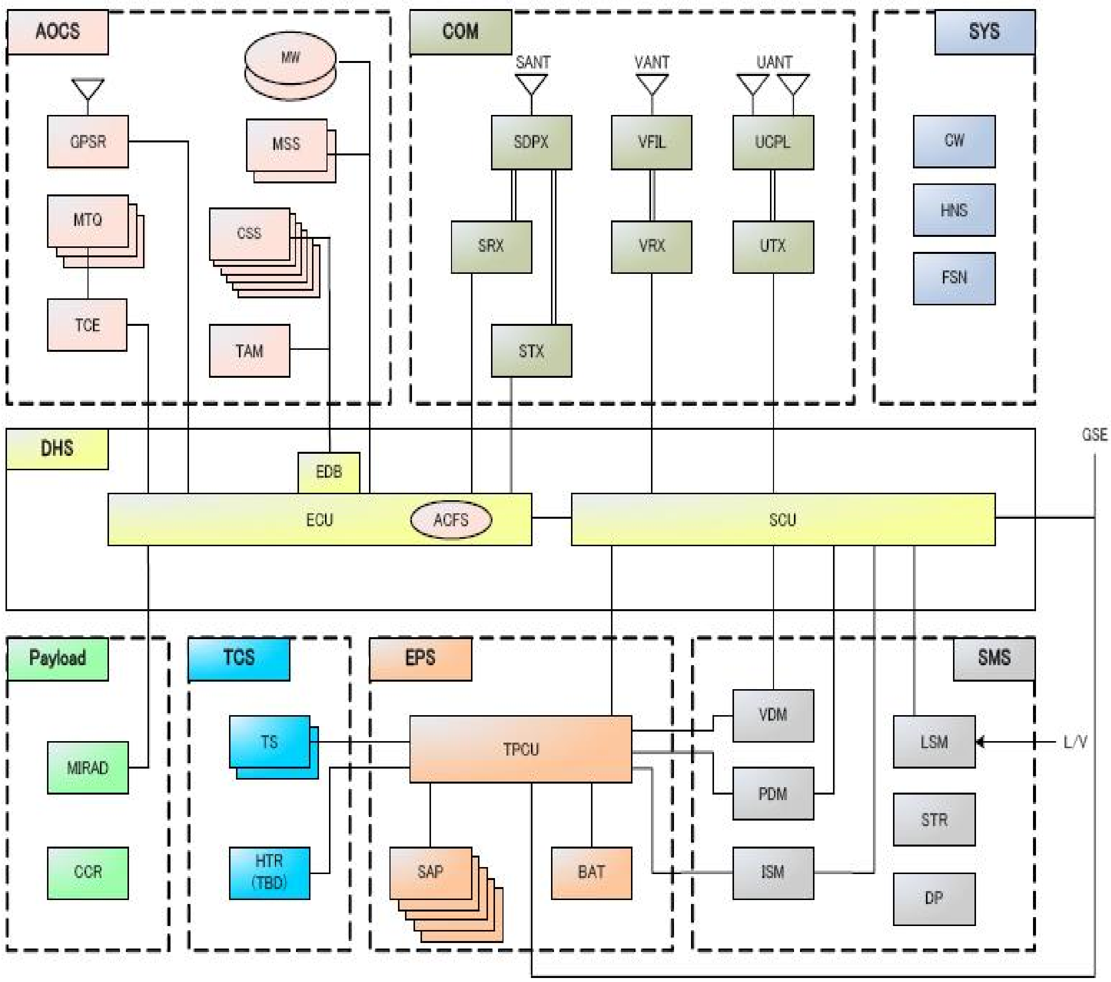

Figure 1: JC2Sat Software Architecture

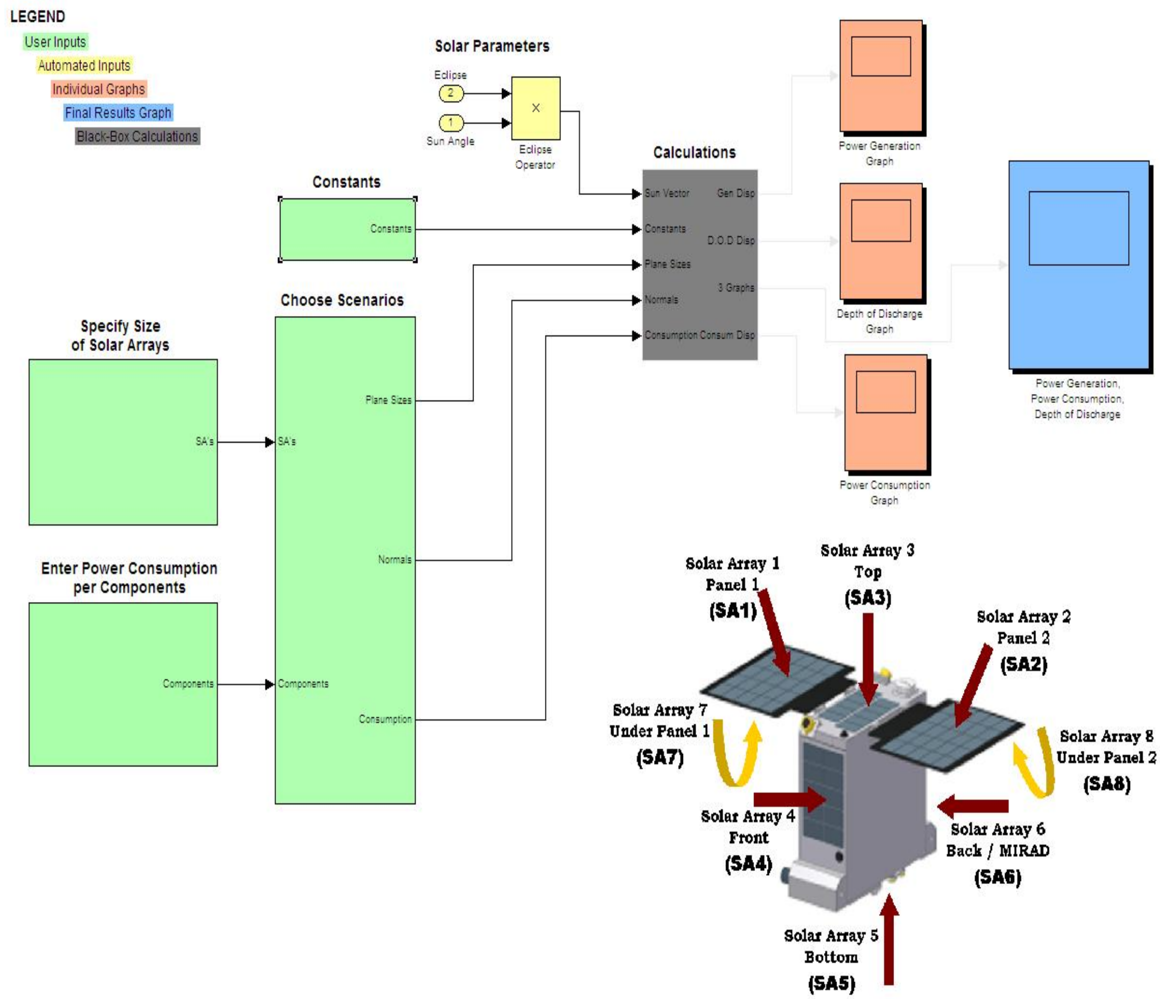

Figure 2: JC2Sat Power Budget Tool in Simulink

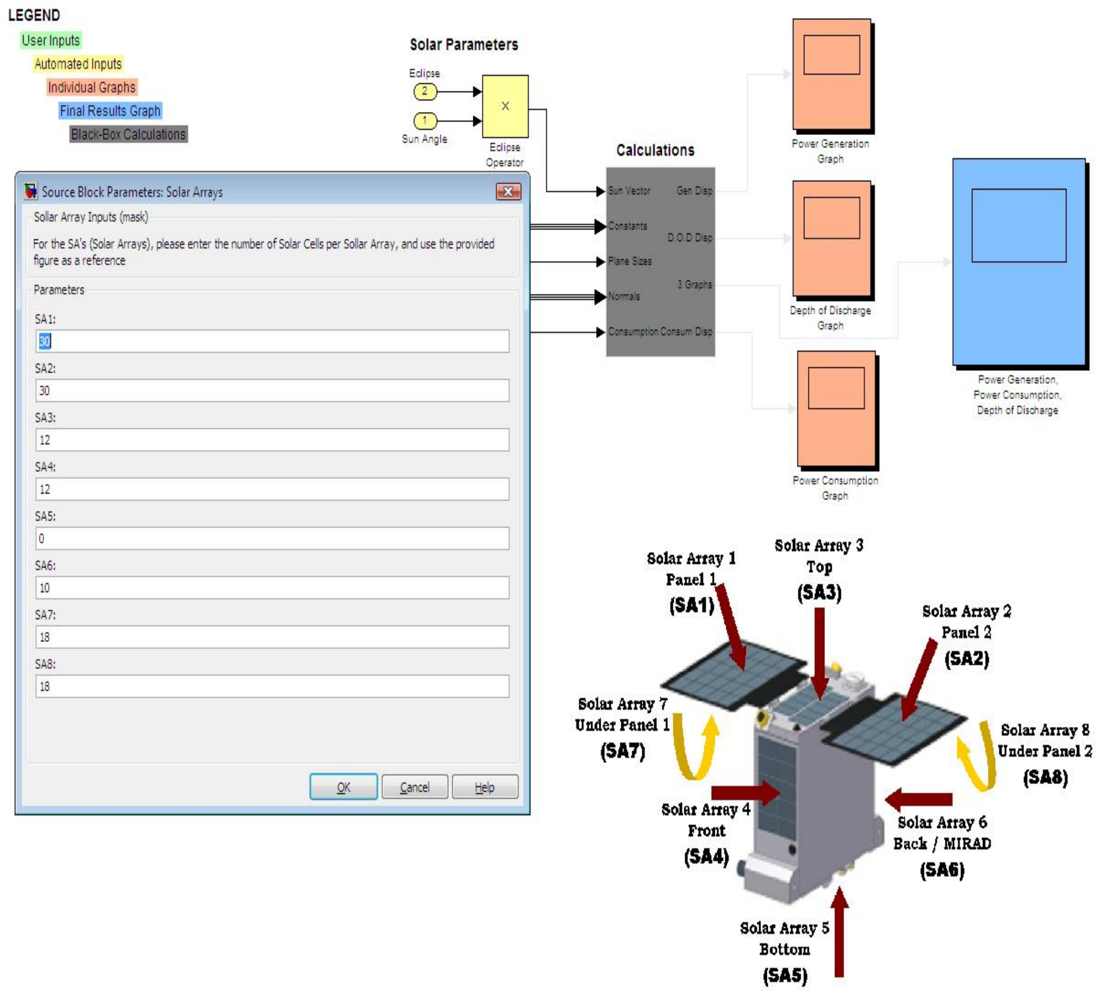

Figure 3: Solar Array Inputs GUI

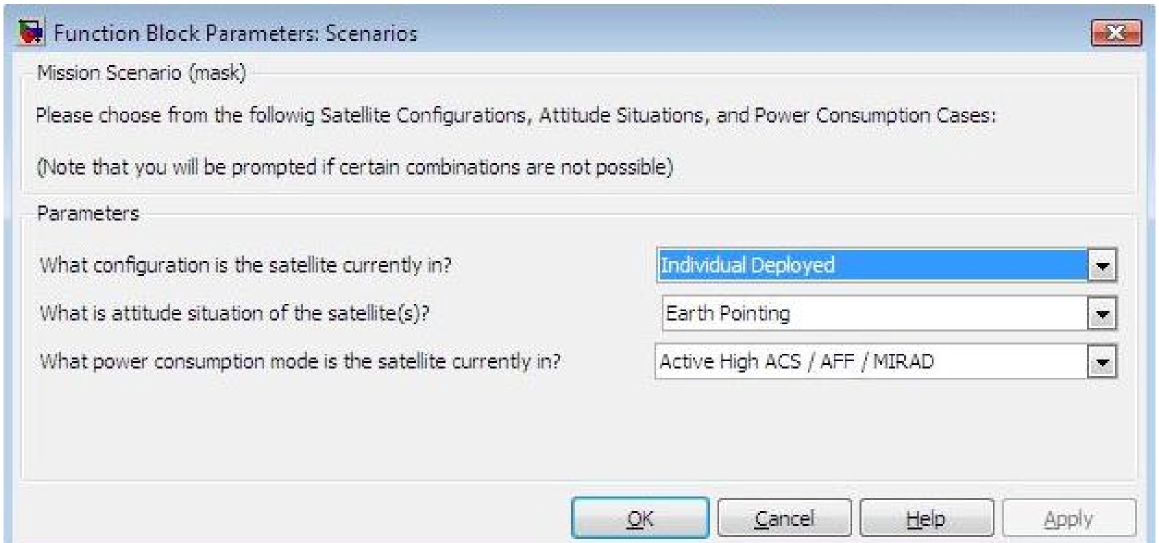

Figure 4: Mission Scenario Inputs GUI

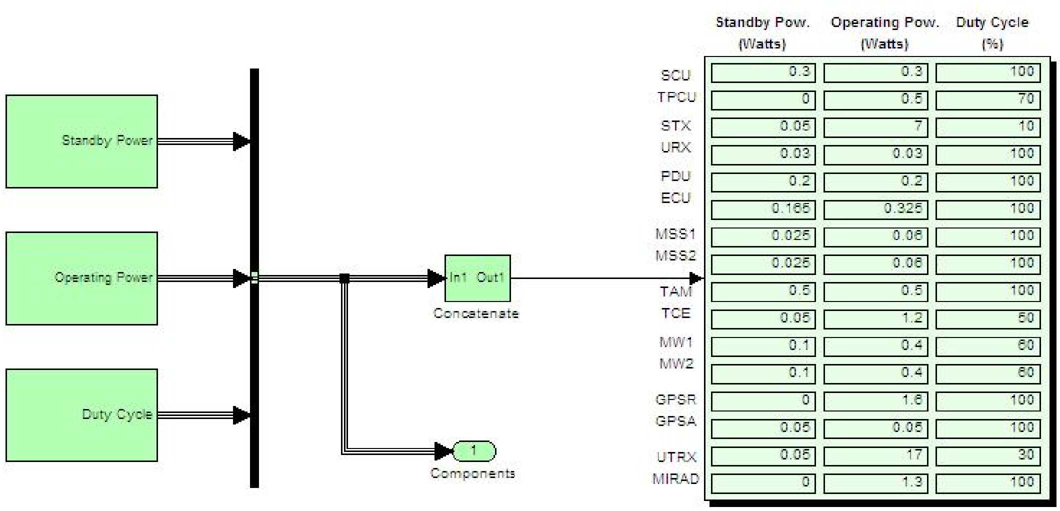

Figure 5: Power Inputs

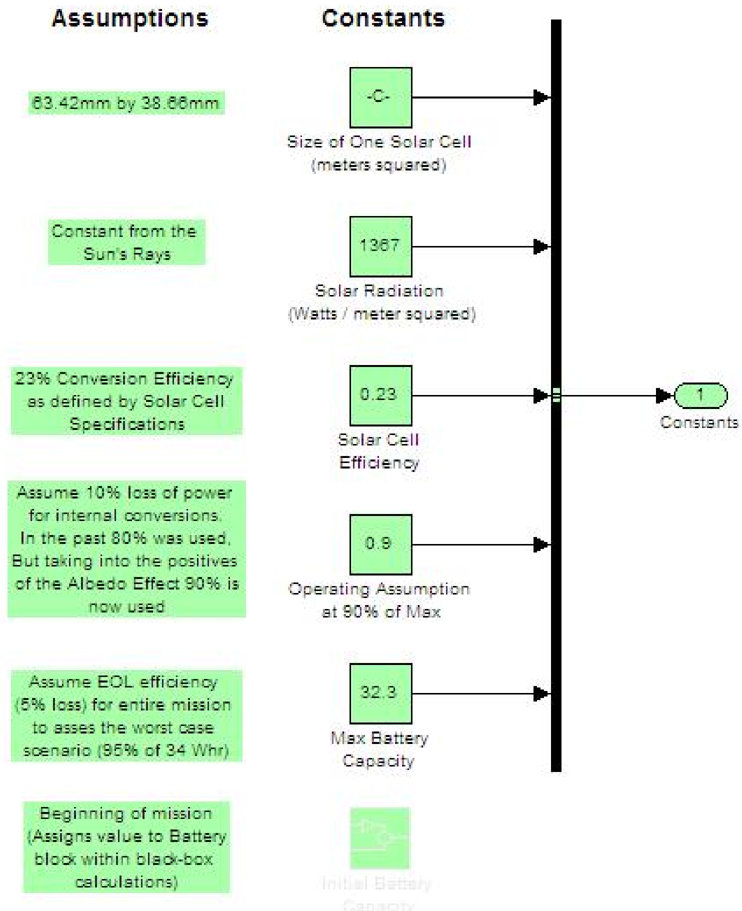

Figure 6: Constants

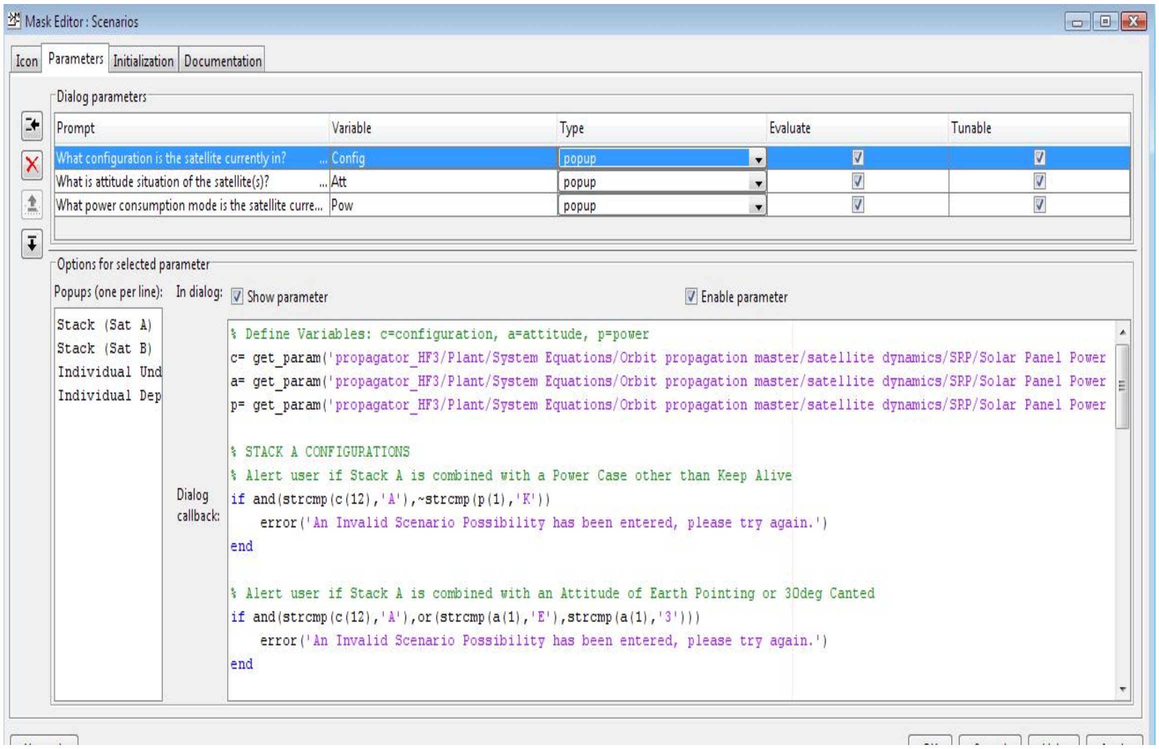

Figure 7: Mask Editor