Blender & STK Power Estimate

Goal: use STK simulation to predict how much power our sat's solar panels would generate in space under different orientation/rotation scenarios.
Completed by: Lukass K., Elijah B., Fall 2024
Working notes on this Discord thread (#mechanical/Blender Power Estimate) (no clue how long this link will work for).

General Overview of Ansys STK:

Sources:

- *STK Website*
- *STK Cloud*

Ansys Systems Tool Kit (STK) provides a physics-based modeling environment for analyzing platforms and payloads in a realistic mission context.

This simulation was carried out using STK 12.7. Contact Andy (prof. Andrew Szymkowiak) for STK license info.

Note that STK requires access to the licensing server at startup and during use (after you open it you can get away with disconnecting from the server for some time, but eventually the app will kick you out!). You need the Yale VPN to access the licensing server outside the Yale Wi-Fi.

Using STK:

Sources:

- *5 part L1 Video Tutorial Series on Using STK*
- *Ansys Government Intiatives (AGI) Channel with Video Resources on STK*
- *STK Help Page with Resources*
- *Problem Specific Tutorial - Solar Panel Simulation (Recommended by Elijah)*
- *Basic Satellite Scenario Design in STK*
- *glTF Models - Adding Solar Panels to the Satellite via articulators*
- *Scenes and nodes in glTF*
- *Adding Articulations for STK*
- *Video Series on glTF Modeling Pipeline - Going from Blender to Ready 3D Model for STK*
- *STK for CubeSats Info Presentation*
- *.gmdf file example for Solar Panel Power Test*
- *How the Solar Panel Tools Works*
- *Quick Video sing the Solar Panel Tool*

General flow of Power Generation Estimation (see also the short guide below):

1) *Create New Scenario in STK*
2) *Insert Satellite Object*
    a) *Use Orbit Wizard to Specify Orbit Params (can use ISS orbit parameters as reference - can download ISS as object from "Standard Object Database")*
        i) *Note: Basically just start with an ISS object and switch the 3D model to that of our sat without changing anything else*

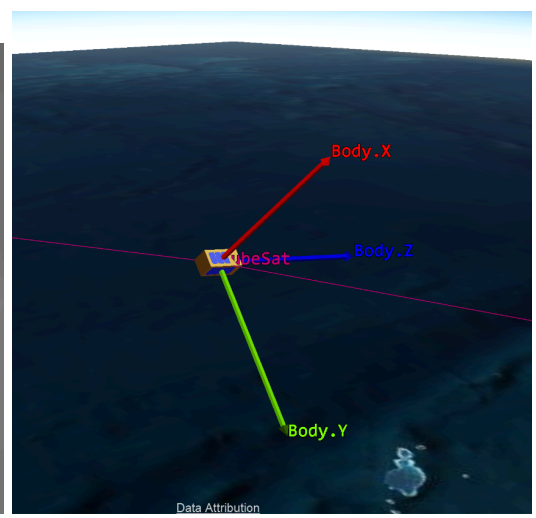
3) *Create Satellite 3D model*
    a) *Use Blender to create satellite outline and Solar Panel Surfaces*
    b) *Export as glTF file*
    c) *In properties of the satellite, in 3D Characteristics import the .glb/.gTIF file*
    d) *Update the STK-native .gmdf (glTF MetaData) file to articulate the Solar Panels also including their efficiency*
4) *Change other satellite properties as necessary*
5) *Set up the satellite attitude parameters*
6) *Run Simulation*
    a) *Go to Satellite->Solar Panels*
    b) *Choose your time sequence*
    c) *Compute*
    d) *Graph/Report data*
7) *Analyze simulation output*

Sat 3D model in Blender:
Sources:

- Measure in Blender

Panels:
The panels are positioned all around the long axis, with 4 cells on each side, except on the positive Y axis, where there is one cell missing (only 3). The cell that is missing is the bottom most cell on the side of the GGB (Gravity Gradient Boom). There are no panels on either of the short sides.

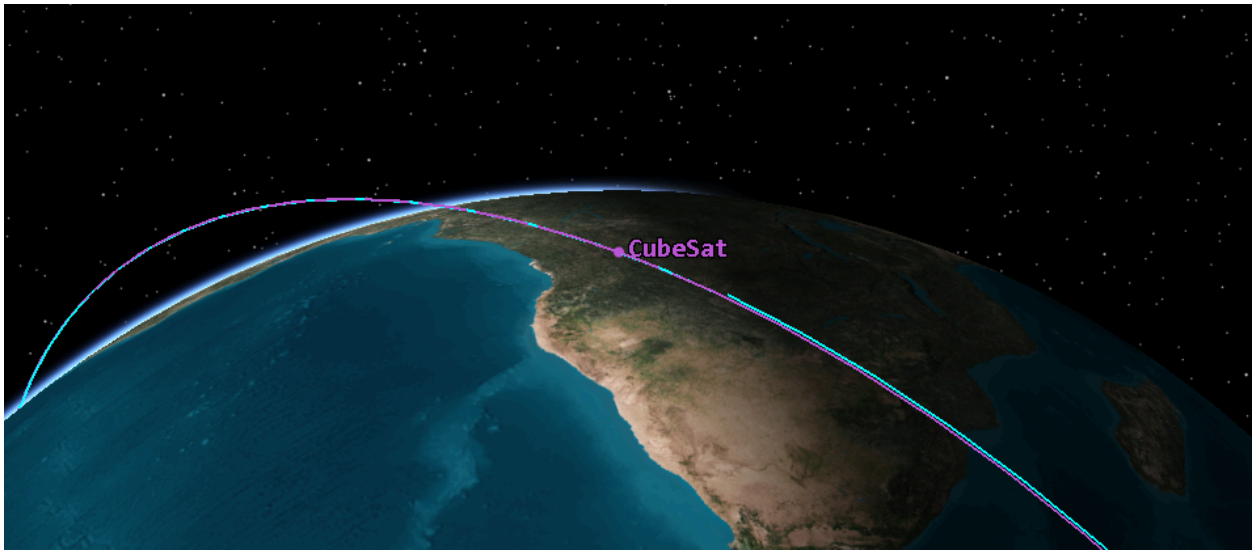
Screenshots of completed sat 3D model. Note that this is a very simple model containing the sat body and solar panel surfaces only, no internal details! Also note that the sat body axes as they appear in STK don't actually correspond with the body axis convention we otherwise use with our CubeSat. This is mostly just an oversight that we didn't fix because it doesn't matter for this simulation.



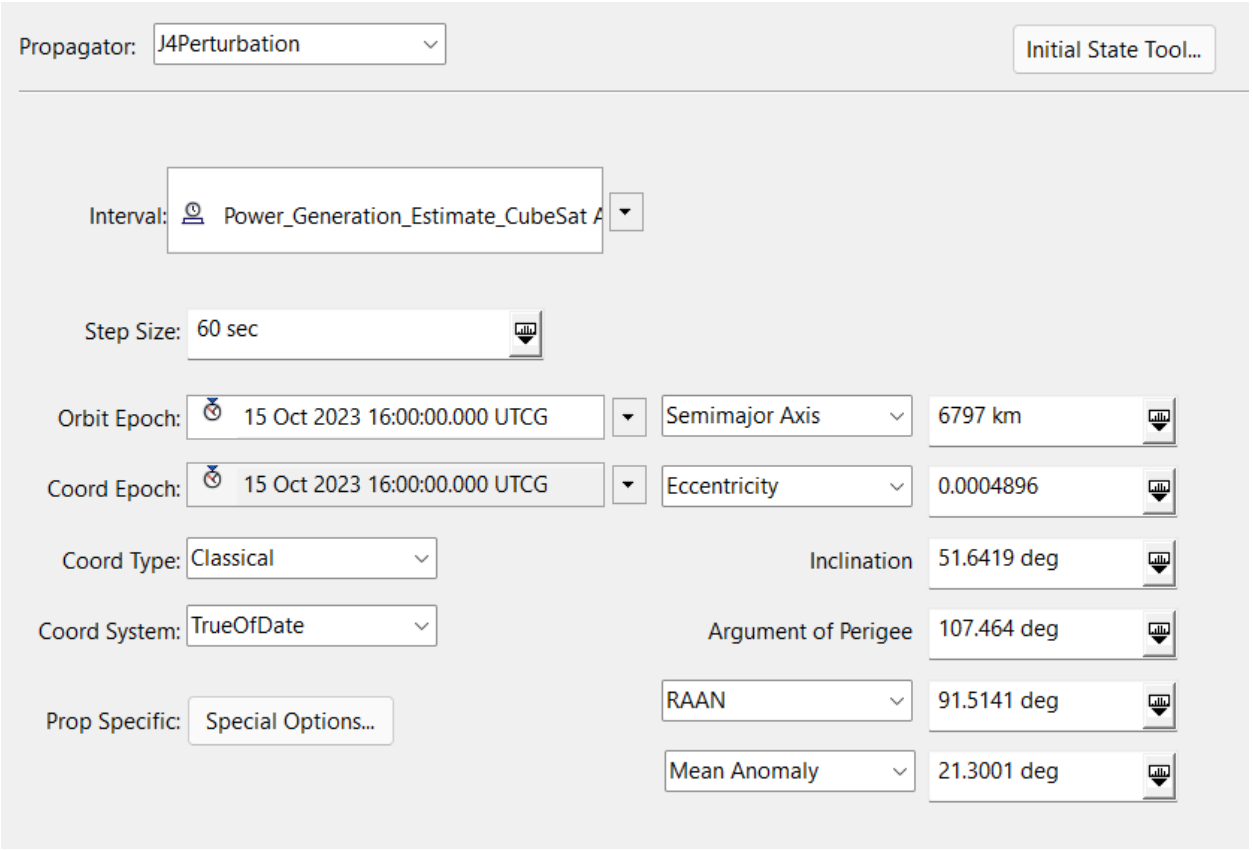
Orbit parameters:

- ISS Orbit Parameters

Use the ISS Orbit by using the SGP4 propagator and use the SSC number for the ISS: 25544



CubeSat Orbit in Comparison with ISS Orbit



Orbit Parameters Used

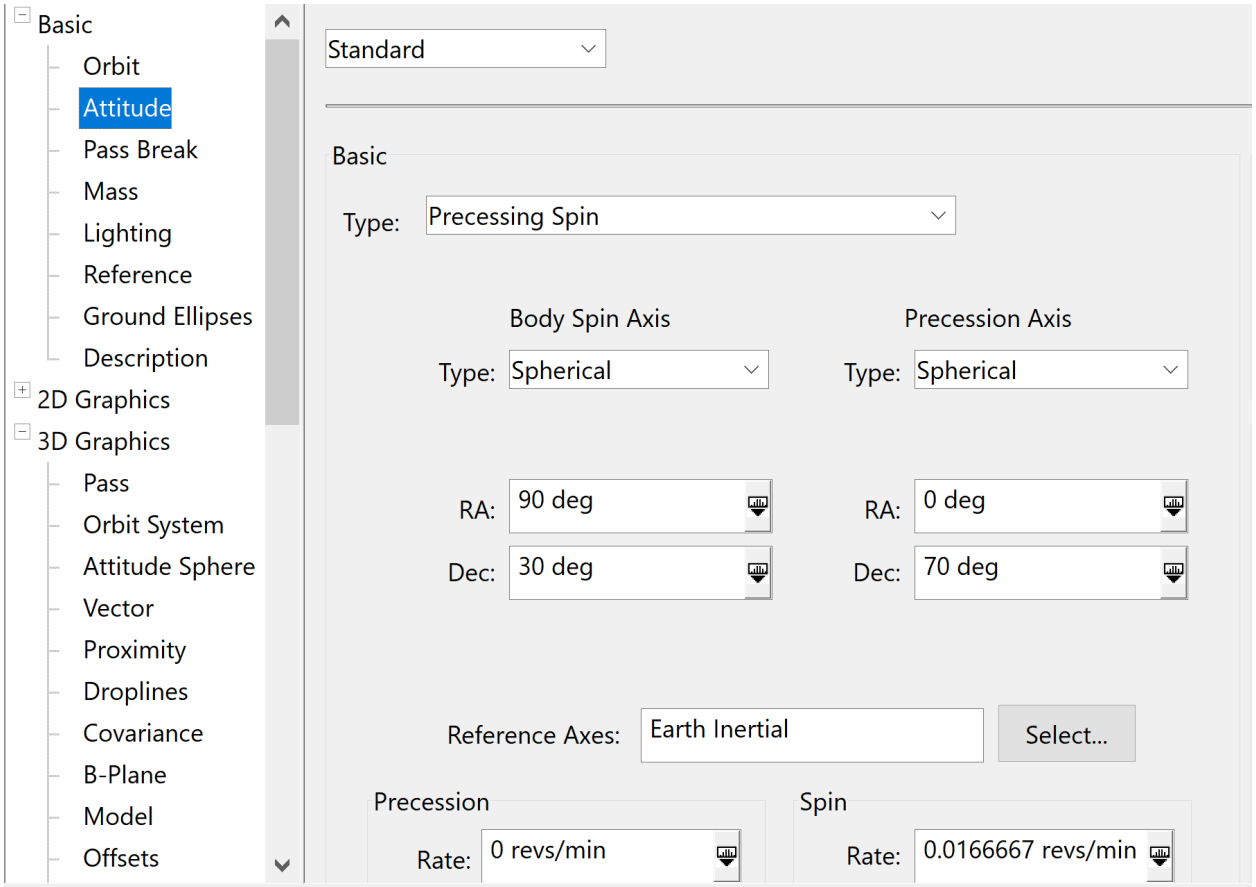
Attitude parameters:

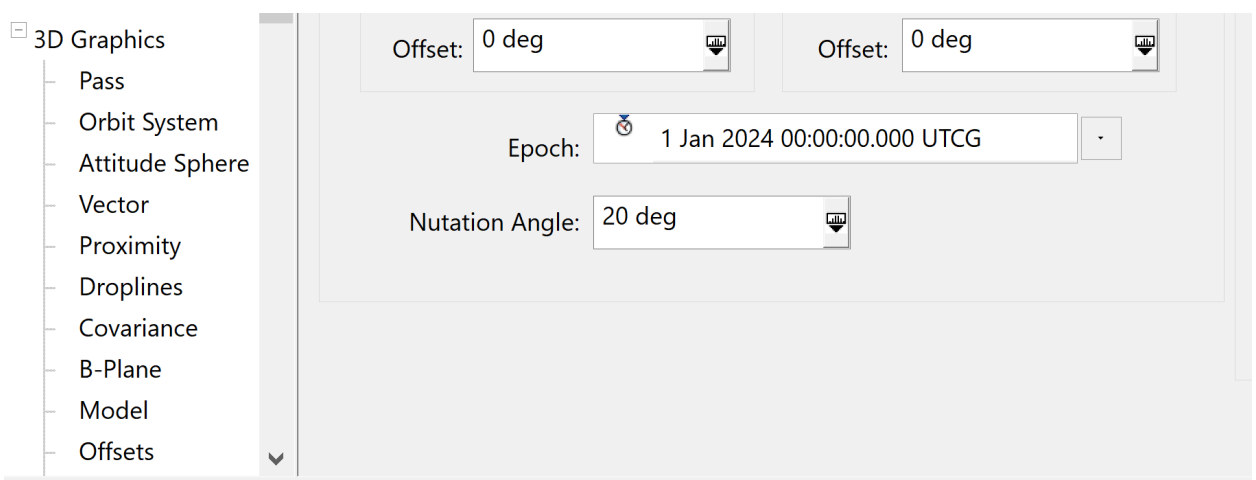
Sources:

- ***See the [ADCS wiki page](#) for a conceptual primer on rotation in space***
- [Defining Attitude Profiles - STK Help Site]
- [Predefined Attitude Profiles]

    - ECF vs ECI velocities
- STK Attitude Sphere
- Coordinate Systems in STK
- Challenges of Spinning CubeSats

In this simulation we mainly use the Precessing Spin attitude type in STK:





Spin Axis:

This specifies the principal axis about which the sat spins. This axis is constant in the sat body frame and that's why its coordinates are specified in the sat body frame.

Precession Axis:

This is the axis about which the sat's spin axis precesses, in other words, the sat's spin axis "cones" about the precession axis. This axis is constant in the Earth inertial frame (or any other inertial frame), and is typically specified in the Earth Inertial frame.

Precession Rate:

Rate at which the sat's spin axis precesses about the precession axis.

Spin Rate:

Rate at which the sat spins about its spin axis.

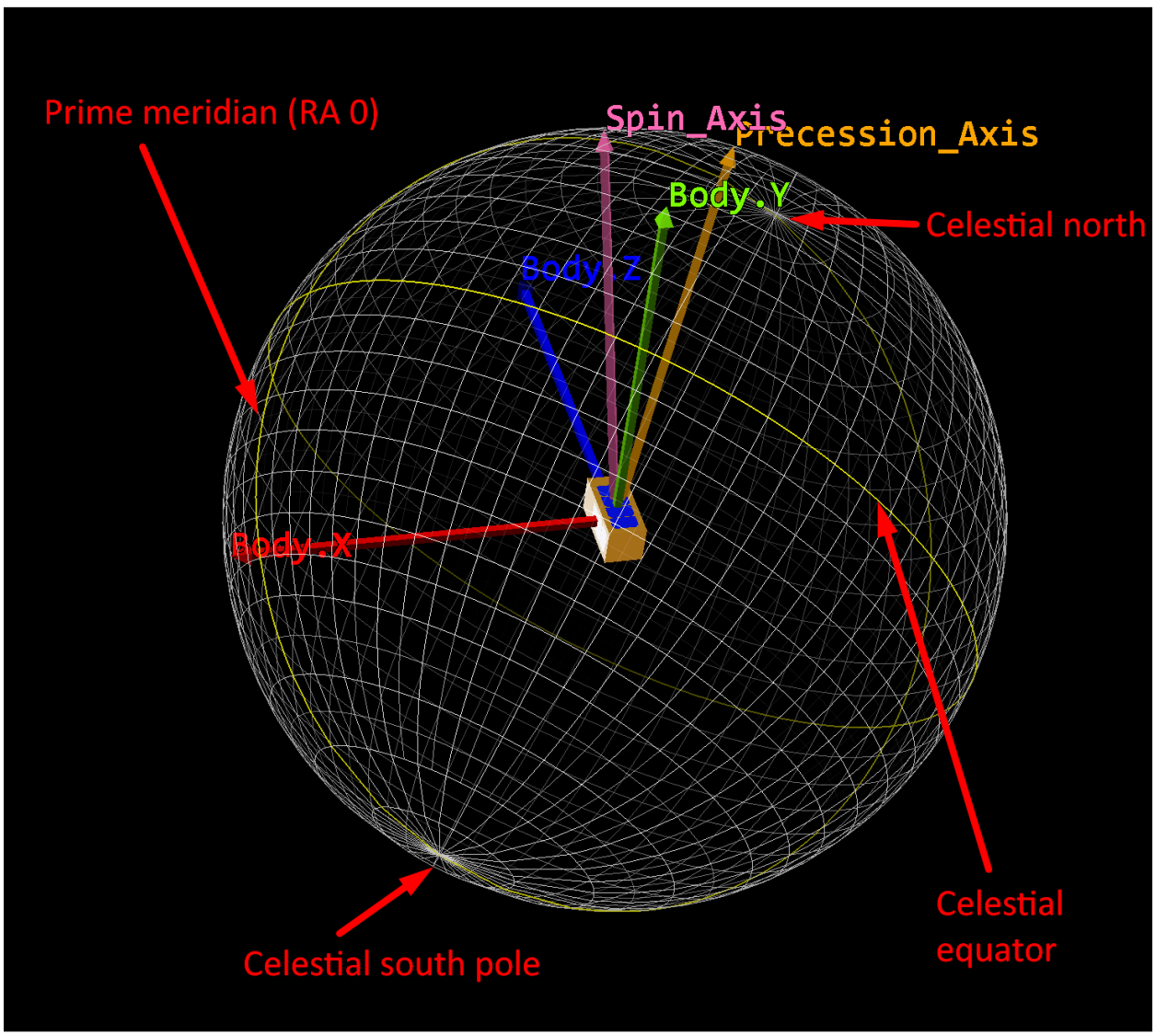
Nutation Angle:

Angle between the sat's spin axis and its precession axis. This angle is constant in time.

Epoch:

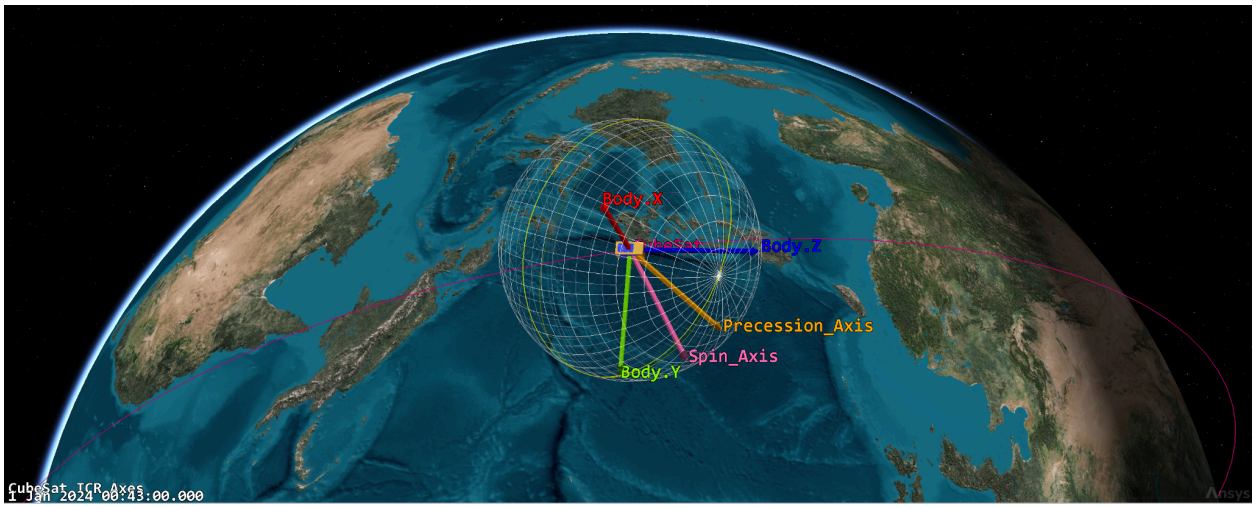
The point in time used by STK as the "time = zero" reference when propagating attitude.

The attitude parameters in the screenshot above produce the following attitude at the epoch time:



This image was made using STK's 3D Attitude Graphics window plus the Vectors property, an extremely useful tool for visualizing attitude.
Note how the sat's spin axis is in the body y-z plane, elevated by 30 deg from the body y axis, because its RA is 90 deg, and those 90 deg are measured from the body X axis, and its Dec is 30 deg, and those 30 deg are measured from the body x-y plane.
Note how the precession axis is close to the celestial north pole, and is on the prime meridian because the RA is set to 0. It would have been precisely at the celestial north pole if the Dec was set to 90 deg (in this case the precession axis would have been exactly aligned with Earth's north-south axis).

Another extremely useful visualization tool is using the STK Attitude Sphere with the sat model and attitude sphere blown up larger than real to see them together with the Earth (this image uses the same attitude configuration):



To reproduce the above:
1. Under Model, set Log Scale to 6 and the Detail Thresholds -> All to 20000km
2. 3D Graphics -> Attitude Sphere, Show, set sphere color to white, Label Type to None, Scale 6.1 and Scale Relative to Model, under Frame select CubeSat -> ICRF. Under Projections, leave the Earth and Sun enabled.
3. 3D Graphics -> Vector, enable Sun vector and Nadir (Centric) vector, and Add... -> CubeSat -> Body -> X,Y,Z. Also Add the Spin Axis and Precession Axis by manually specifying their coordinates. Set Thickness to 10 and under Component Size, check Scale Relative to Model and set scale to 6.2

Conducting Power Generation Estimation:

Sources:

- *Pumpkin Solar Panel Design Guidelines (with efficiency)*
- *Solar Cell Datasheet*
- *CubeSat Coordinate Convention*
- *CubeSat Solar Panel Sizing*
- *Full Assembly*

Parameters:

- Solar Cell Efficiency: 30.7%

Nomenclature:

Sun phase: an uninterrupted interval of time during which the sat is in sunlight as opposed to in Earth's shadow.
Dark phase: the opposite of sun phase.
Theoretically there is one sun and one dark phase per each 90min orbit.

Test Scenarios:

1. detumbled sat (i.e. its rotation is tidally locked with the Earth so that the GGB is always pointing towards Earth. No spin at all.
2. Same as 1 but with spin along sat long axis.
3. randomly tumbling sat, relatively fast rotation rate simulating conditions right after deployment
4. randomly tumbling sat, relatively slow rotation rate simulating conditions right after active detumbling
5. worst-case: sat is not rotating at all and starts in an orientation where its long axis is parallel to the vector to the sun, so that only one of the square faces sees the sun

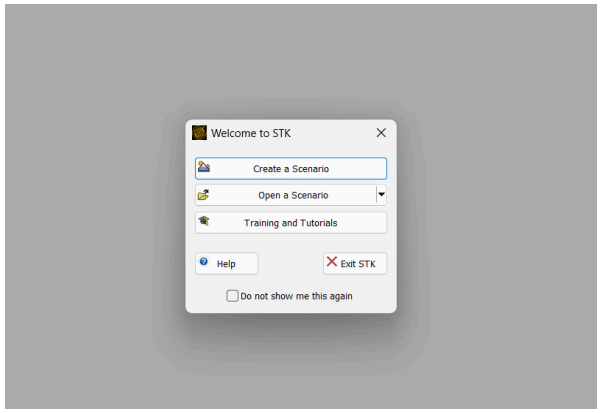
Duration and time step:
Every simulation is run from 00:00 UTCG Jan 1 2024 to 00:00 UTCG Jan 1 2025.
Time step used for solar panel simulation was 2-5 min (the differences in results between simulation runs with the exact same parameters but different time steps were tested to be negligible. The exception is if you want accurate instantaneous power profiles of one sun phase, in which case 2min or shorter is required.)

Questions to answer for each scenario:

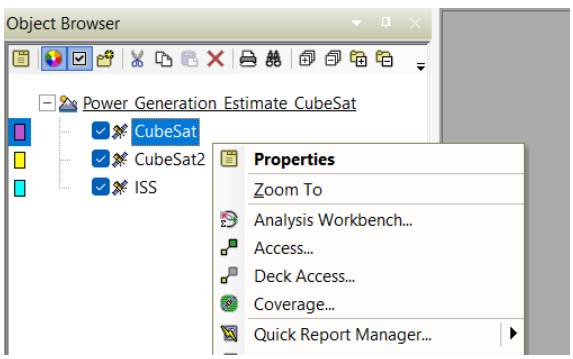
1. *What is the "long-run" average solar power generation over one year?*
2. *What are the "short-term" (on the scale of one day) extremes?*
3. *Is there seasonal variation?*
4. *How much energy is typically harvested every sun phase?*
5. *What does the instantaneous power profile look like? Are durations of sun phases constant throughout the year?*

How to setup a simulation (short guide):

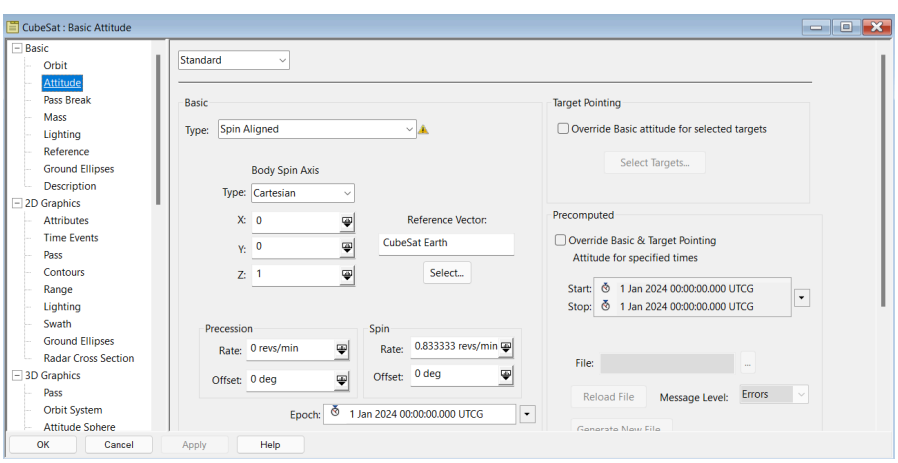
1. Upon starting STK you will see the following window - click on **“Open a Scenario”** and find the scenario file **“<scenario_name>.sc”** - this will load the scenario - the context within which you are simulating:



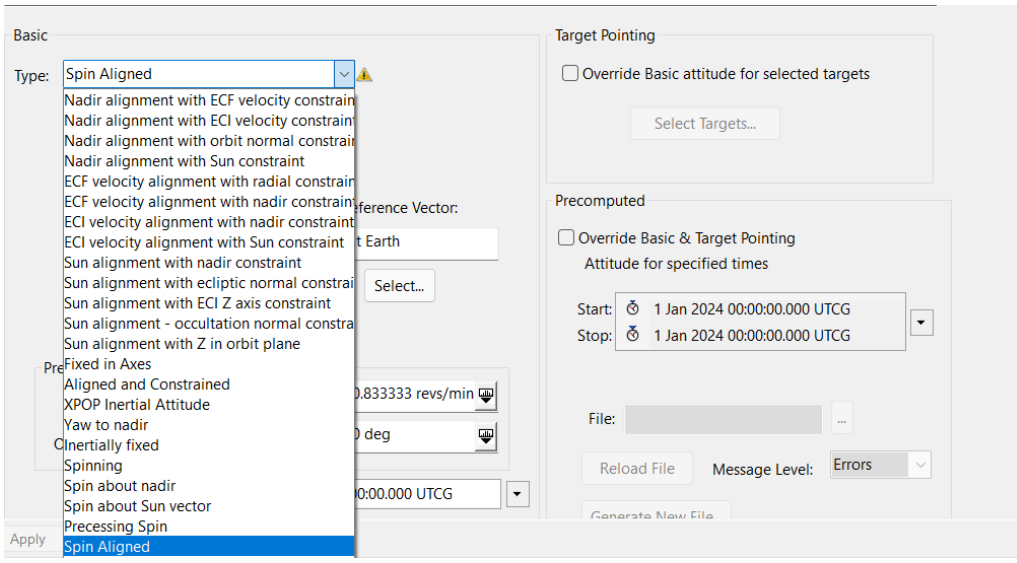
2. On the left side - you will see the Object Browser with all of the satellites currently in the simulation. Right click on the CubeSat to be simulated and select **“Properties”**.



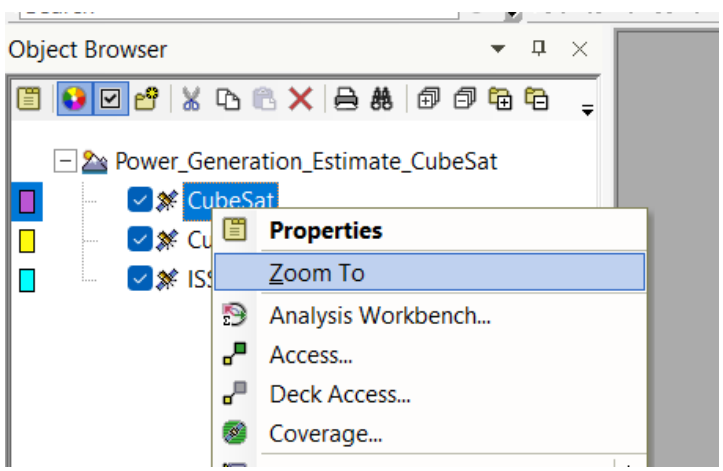
3. The properties window is the panel where you will set all the main parameters of the satellite and simulation. In our case we only change the “**Attitude”** section of the CubeSat - which you can navigate to from the dropdown menu on the left side of the properties window.



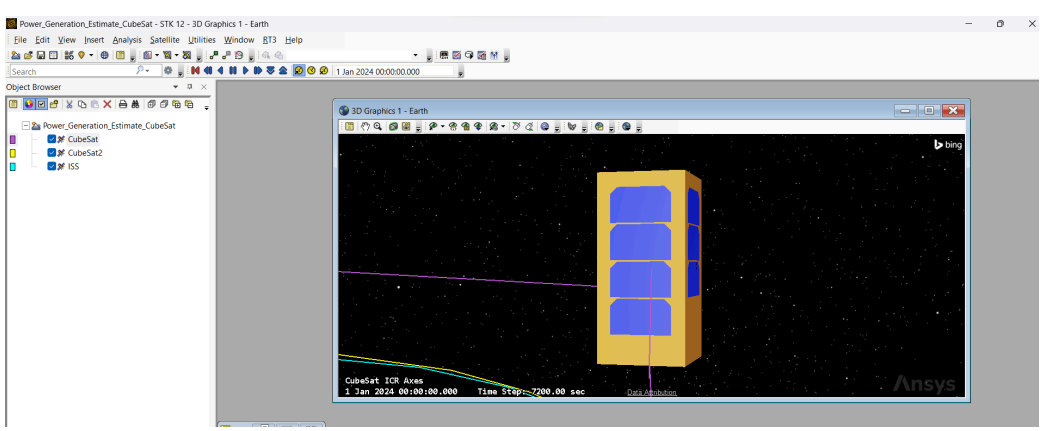
4. To define different attitude scenarios first select the **"Type"** of the attitude description you will use from the menu and then change all the relevant parameters. (For spin aligned this would be precession rate, spin rate, etc.)



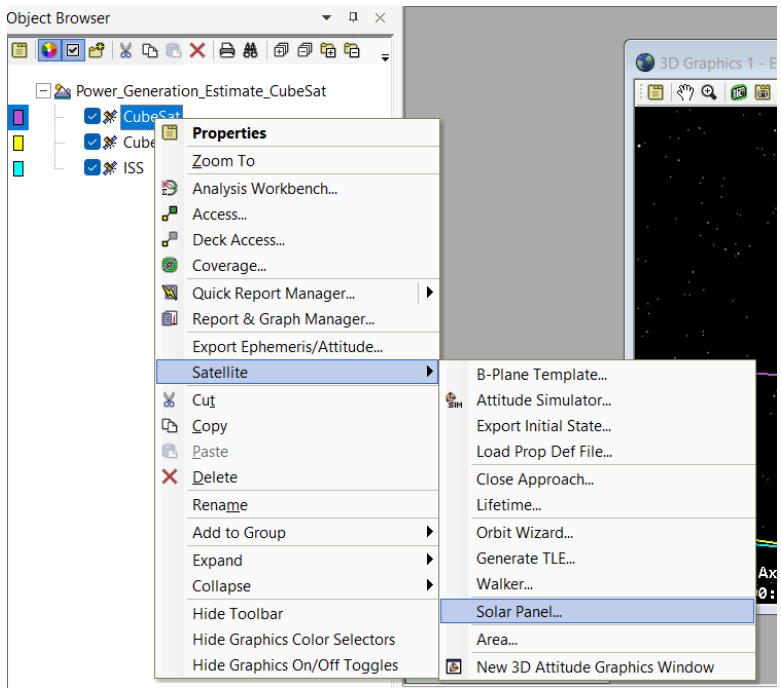
5. Once you have finished setting all the attitude parameters, click apply and okay on the left corner of the Properties window.
6. Then it will probably be useful to double check the attitude behavior of the satellite. You can do this by viewing it in the 3D view by zooming into it. To do this once again right-click on the satellite and select **"Zoom To"** in the menu. This will automatically zoom in on the satellite in the 3D view.



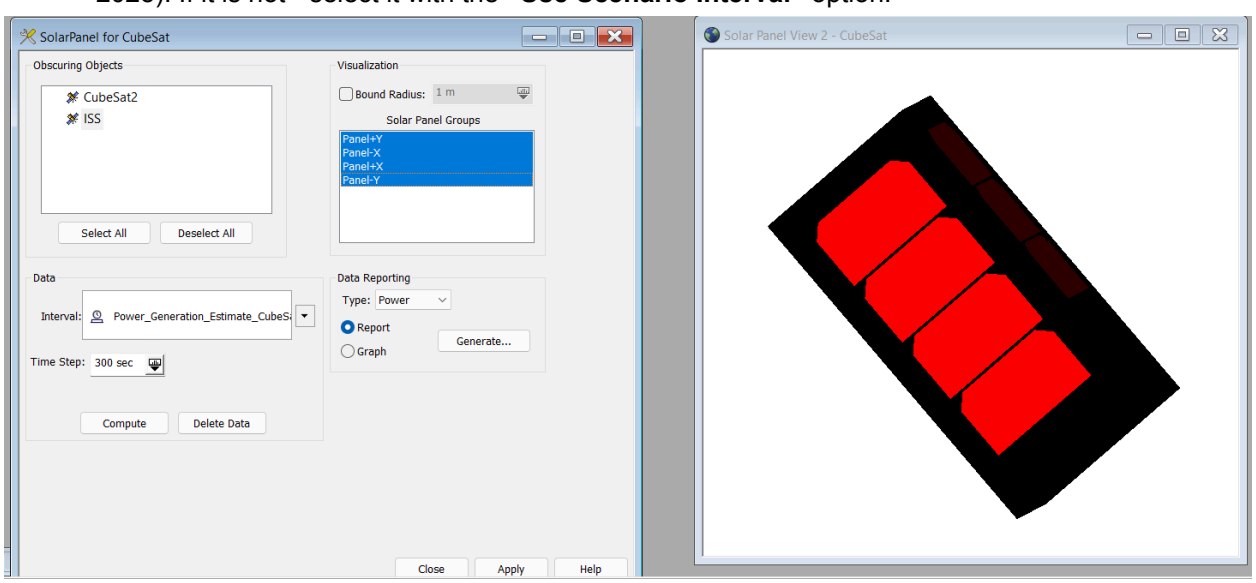
7. To see the satellite in motion, press on the blue triangular start button at the animation menu right above the gray window area.



8. If everything is correct, you are ready to simulate. Right click on the satellite and select the **“Satellite” -> “Solar Panels”** option.

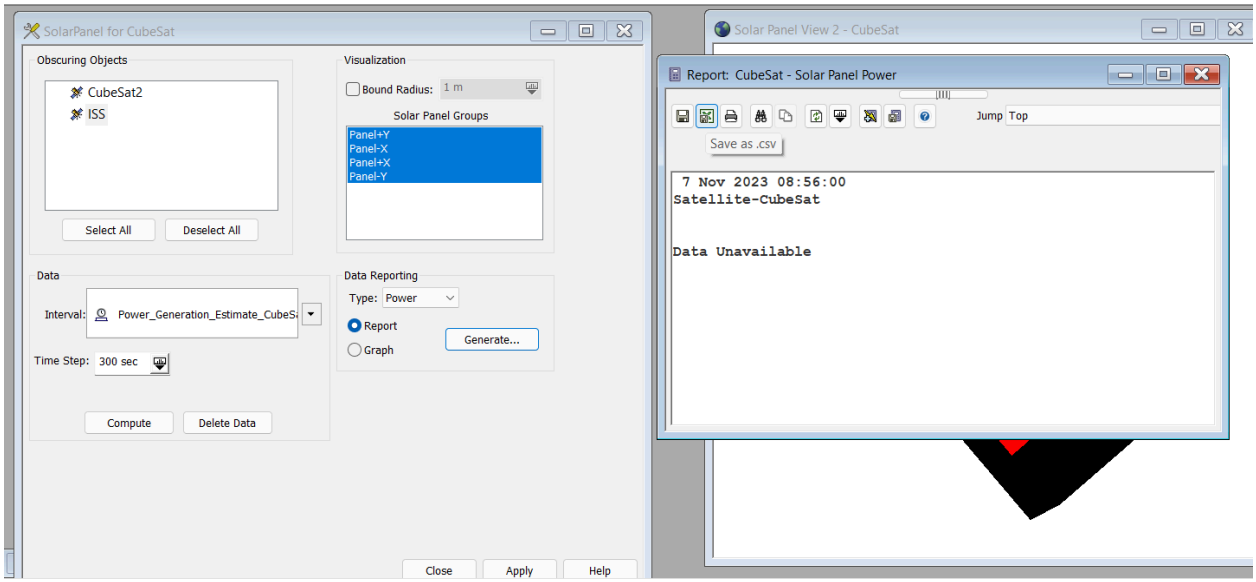


9. Two windows will open: The Solar Panel Simulation Configuration window and the Solar Panel View Window. In the Configuration window select all Solar Panel Groups and double check that the Simulation **“Interval”** is set to the entire scenario interval (from January 1 2024 to January 1 2025). If it is not - select it with the **“Use Scenario Interval”** option.



10. Finally you can click **“Compute”**, which will start running the simulation. The simulation runs as an animation and you can see it progressing over the year in the various windows (as well as in the animation pane in the lower part of STK). The animation rate and speed is linked to the simulation, so don’t toggle anything about the animation while the scenario is running (say increasing the rate of animation) as this will affect the simulation (for example give less time resolution).

11. Once it has finished. Click on **“Generate”** in the Solar Panel Configuration Window. This will open a textform report with all the data of the simulation. Find the button called **“Save as .csv”** and save the data from the simulation in a .csv file. Then the simulation is complete.



Data Analysis Process

Short Overview of Data Analysis Process:
Analysis of the CSV report generated by STK is automated by the Python script analysis.py. Before running the script, make sure to set up the simulation ID and filestructure as described on line 16 of the file.

What the script does:

1. Extracts all data from main data .csv file to separate .csv files with data on each panel separately and all panels together (saved in Split directory).
2. ***What is the average solar power generation over one year?***
    a. *Process:*
        i. *Integrated over all data points to get total energy and divided by time*
    b. *Result:*
        i. *Numerical value of average power over year (W)*
3. *What is the range for averages over one month?*
    a. *Process:*
        i. *Found all the indexes in data list for start of each month*
        ii. *Used this to calculate average power over each month (W)*
        iii. *Plotted results in bar graph*
    b. *Result:*
        i. *Range of averages over 1 month - maximum and minimum value*
        ii. *Bar plot of average power generated in each month ("avgyear.png")*
4. *What is the range for averages over one sun phase?*
    a. *Process:*
        i. *Using sun intensity boolean value (serves as good indicator of sun phase - when in sun, has value 1, when not, has value 0) - differentiated and got data on all the sun phases in the simulation period, which were processed into 3 lists:*
            1. *Average power over sun phase (W)*
            2. *Duration (min)*
            3. *Index of start of sun phase in real data list*
        ii. *Extracted max and min values for average power over sun phase, found the date of occurrence of these sun phases*
    b. *Result:*
        i. *Range of power averages for all sun phases - maximum and minimum value*
        ii. *Plot of power averages of all sun phases throughout the year ("sunphaseavgs.png")*
5. *What does the sun-dark profile look like i.e. how long are sun and dark phases and is that constant throughout the year or not?*
    a. *Process:*
        i. *Using data obtained in step 3ai) extracted max and min values of duration of sun phase*
        ii. *Made way to filter out very large and small duration sun phases and create a list of "normalized" sun phases*
        iii. *Found and plotted average sun phase durations for each month (calculated as sum of all durations divided by amount of sun phases in month)*
    b. *Result:*
        i. *Range of duration averages for all sun phases - maximum and minimum value*

ii. *Bar plot of average sun phase duration in each month (“sunphasedurationsyear.png”)*

iii. *Plot of durations of all sun phases over year (“sunphasedurations.png”)*

6. *Other results:*
   a. *Plots of power of each panel separately and all panels together for each month of the year (folder “Months”)*

Example of console printout:

```
Read all files, line length is: 105409
Simulation time is: 31622700 seconds = 366 days
Average Power over 1 year: 2.976
Range of averages over one month: 2.481-3.521 W
Range of sun phase power averages: 1.303-5.407 W
Range of sun phase durations: 10.000-7360.000 min
Average power max index is 1528 at time 8 Apr 2024 15:35:00.000
Average power min index is 1532 at time 8 Apr 2024 19:30:00.000
Duration max index: 5199 at time 7 Dec 2024 00:20:00.000
Duration min index: 1528 at time 8 Apr 2024 15:35:00.000
Range of sun phase duration averages over one month: 92.570-111.085 min
Plotting month graphs...
Done
```

Results & Discussion

See the raw and analyzed data here.
See the power demands calculations here. The analysis here uses the following benchmark values (note that these are not cumulative - read about how power levels work on the CubeSat wiki):
- Power needed to at least stably run the CRD (L4): 3 Wh per orbit or 2 W averaged power
- Power needed to at least stably run active detumbling (L3): 2.4 Wh per orbit or 1.6 W averaged power
- Power needed to at least maintain stable radio contact (L2): 1.3 Wh per orbit or 0.9 W averaged power
- Power needed to at least prevent the EPS from freezing (L0): 0.5 Wh per orbit or 0.35 W averaged power

Efficiencies

Solar cell efficiencies are taken into account by STK.

The solar cells will also lose efficiency as they heat up. According to the solar cell datasheet, we lose 26% of the MPP voltage and gain 3% of the MPP current at 125C compared with nominal values (reported at 28C). This pretty much translates to a 25% reduction in efficiency. Very probably the panels will get that hot towards the end of a sun phase and will probably cool down to much closer to 30C before the start of the next sun phase, but being any more precise requires some kind of simulating of the sat temperatures. For the purposes of analyzing the power budget, as a worst-case limit all the production values reported by STK should be reduced by 25%.

The efficiency of the EnduroSat EPS battery charging regulator is ~95% so we neglect this as it is within the error of predicted consumption and measured production anyway.

The efficiencies of the EPS voltage converters is taken into account when calculating power demand.

Overall

Seasonality

The sat's orbit precesses around the Earth with a roughly monthly period. We are not sure what causes the orbit to precess (maybe the Moon?) but we tend to trust STK on this (note that the precession of the orbit is not affected by varying the CubeSat's mass between ~1kg and ~10000kg). Often this precession also leads to oscillations in the solar harvest, though the degree of oscillation is heavily dependent on the sat's attitude.
Usually, twice per year the precession of the orbit results in a configuration where the sat's orbit is face-on towards the sun (i.e. the orbit normal is almost parallel to the vector from the Earth to the Sun). When this happens, the analysis script will show an abnormally long sun phase with a duration exceeding several orbits as the sat is continuously in the sun.

Sun phase durations

Sun phases are 60 min long with very high consistency (excluding of course the above mentioned long sun phases). This differs significantly from the assumption that the sat's 90 min orbit is split half-half between light and darkness, presumably due to the sat's considerable altitude above the Earth.

Scenarios 1 & 2 - tidally locked sat

Long-run performance & typical harvest

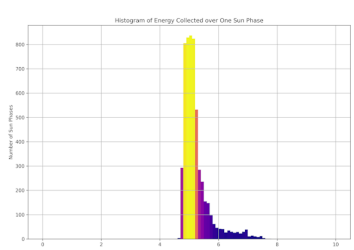
Both scenarios agree on a month-averaged power generation around 2.75 W, falling as low as 2.5 W and rising as high as 3.5 W. Meanwhile, the sun phase energy histograms differ significantly between these two scenarios. We see that a lack of spin produces a worrying downside extending well below 3 Wh per

sun phase. Interestingly, the histogram of Sc1 shows twin peaks, which is probably due to a resonance as the sat's lack of spin makes seasonal variations come through undamped. The histogram of Sc2, which is much closer to plausible orbit conditions, has a single spikier peak around 3.75 Wh per sun phase with no significant downside and an upside up to 5 Wh. The upside in both these histograms likely comes from the face-on orbit configurations when the sat is consistently in the sun for hours at a time. Overall, accounting for solar cell thermal efficiency loss, in this scenario we should be able to run the CRD for most of the time, though we will likely incur a few weeks of downtime per year during the "lean months" when the sat's orbit is edge-on to the sun, causing the sat's long sides to see relatively little sunlight. Core system functions are however not endangered.

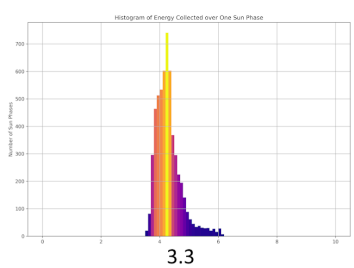
<u>Extremes & seasonal variation</u>
Monthly variation is more significant for the not-spinning Sc1 than for the spinning Sc2, which makes sense since a spin would smooth out variations in solar incidence angle. Overall however, these scenarios see relatively little seasonal variation (~20-25% for Sc2) with no dangerous low extremes.

<u>Power profile</u>
As expected, the sun phases begin with a power peak, have a trough in the middle, and end with another peak. This makes sense as a tidally-locked sat's long sides will have good solar incidence around the start and end of a sun phase when the sat's long axis is perpendicular to the vector to the Sun, while in the middle of the phase the solar panels will present very little area to the sun. The variation in instantaneous power is very dramatic (1-6 W), and the sun phase time is split roughly evenly between high and low power.

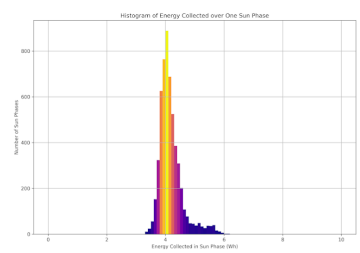
Scenarios 3 & 4 - tumbling sat
<u>Long-run performance & typical harvest</u>



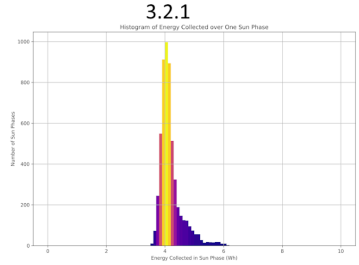
3.2.1



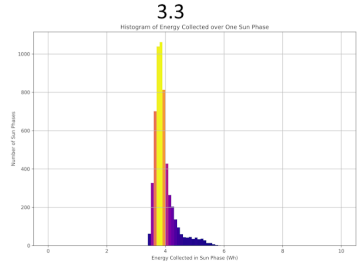
3.3



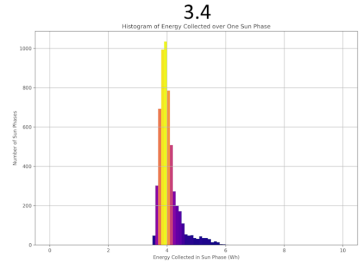
3.4



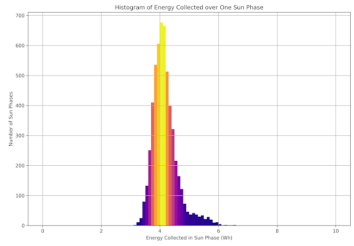
3.5



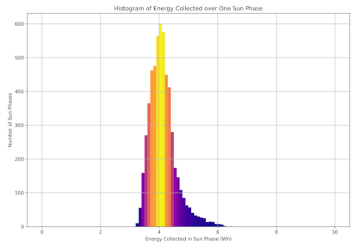
3.6



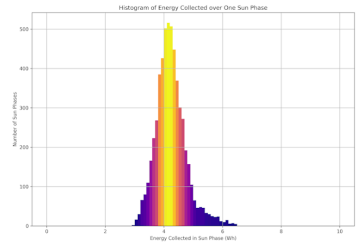
3.7



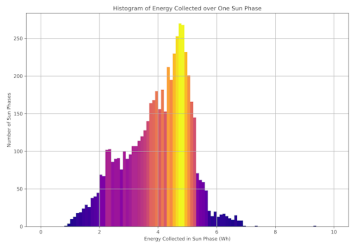
4.1



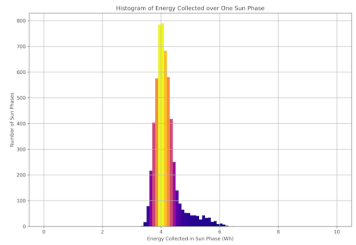
4.2



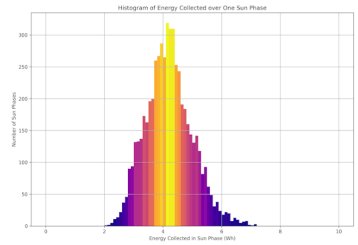
4.3



4.4



4.5



4.6

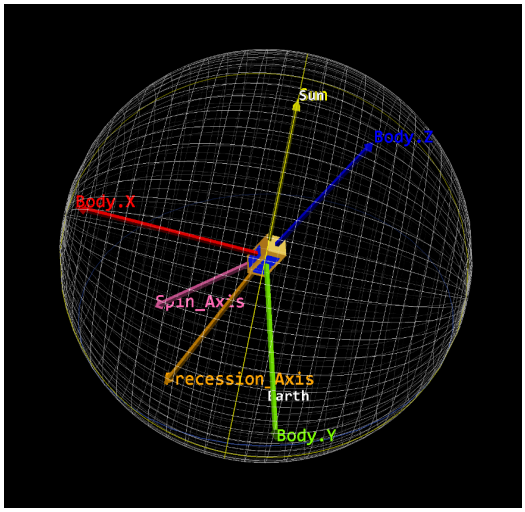
As expected, almost all of the 12 simulation runs are very consistent, and furthermore, the histograms for Sc3 are generally more concentrated than those for Sc4. With a fast spin, the attitude changes so much during a single sun phase that each sun phase's performance is smoothed out, but with a lower spin, variations between phases become more apparent. Typically we collect just about 4 Wh per sun phase (long-run average generation ~4 W), which is definitely enough for us to either do active detumbling or run the CRD. If we can get the OBC CPU consumption down substantially, and thermal efficiency losses are merciful, we might just have enough energy to do both at the same time. Furthermore, the downside is limited to 3 Wh per sun phase, which with thermal efficiency loss is probably not enough for neither the CRD nor active detumbling but still doesn't endanger core system functions.

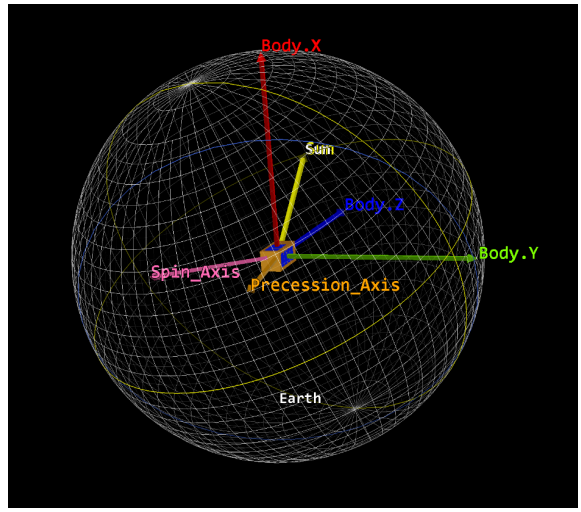
Sc4.4, however, has a long downwards tail extending to around 1 Wh per orbit, which already significantly endangers radio contact stability. Examining its plot of average sun phase power, we see two large dips per year.

Sc4.6 meanwhile has the same center as the other 4.x scenarios, just broader, and we also see that its avg phase power curve is substantially noisier. This difference is likely just caused by the fact that the spin rate of 4.6 was forced to be the minimum in the range i.e. 0.05 deg/sec, which is at least 2x slower than all the other 4.x scenarios.

<u>Extremes & seasonal variation</u>

The average sun phase power curves and monthly average power bar graphs for Sc3.x and 4.x typically show very little seasonal variation, which makes sense as described above. This is very different for Sc4.4.





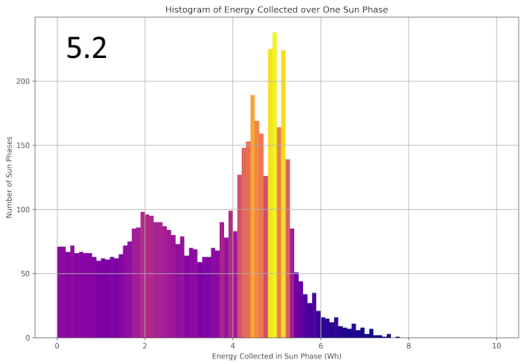
These two attitude sphere views for 4.4 are taken on May 28 2024 (around the time of the first big dip) using the Sun EclpJ2000ICRF frame for the attitude sphere. The "equator" of this sphere is the ecliptic plane and the poles are the solar system north and south poles.
We see the following set of bad news:
- The precession axis lies close (~20deg) to the ecliptic plane and the nutation angle (angle between precession axis and spin axis) is small;
- The spin axis is pretty much the sat's long axis

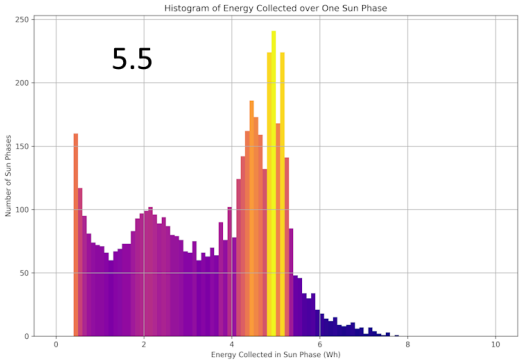
Together these factors mean that the sat's long axis is always close to the ecliptic plane, and that means there will be two times per year when the sat is square face-on to the sun and gets very little power for a couple weeks at a time.
Notice that this condition is not related to spin rates but only to the spin and precession axes and the nutation angle, which are probably basically random for us since they will be determined by which way the NanoRacks deployer is facing during deployment and the minute force imbalance of the deployment springs.

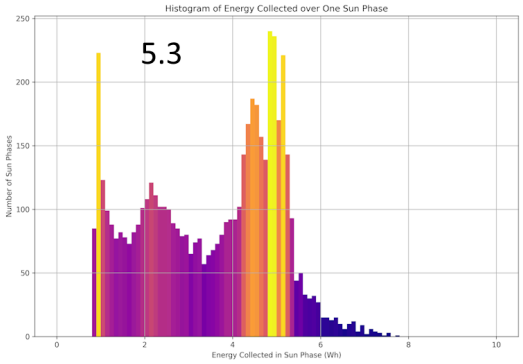
<u>Power profile</u>
As expected for a rapidly spinning sat, the instantaneous power profiles are consistently all over the place with variations within 2-6 W happening over a few minutes. The phase profiles for most 4.x scenarios are a little smoother, except the profiles of 4.4 and 4.6, which have slower spin rates, and are a lot smoother, with 4.6 being just one smooth sine curve.

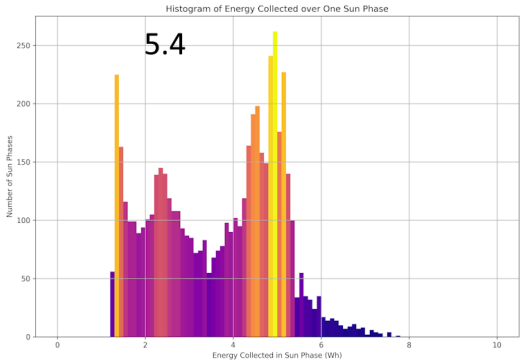
Scenario 5 - worst case
For Sc 5.2, the sat's long axis is specifically set to always remain within the ecliptic plane with no precession and slow spin. As a result, we see that around the vernal and autumnal equinoxes the power literally drops to zero as the sat’s long axis points exactly towards the sun and the solar panels present zero area to the sun. The long backwards tail of the histogram is looking real bad and from a really rough integral, we're below the L4 CRD level (~3Wh per orbit) about 40% of the year and below L2 stable radio level (~1.4 Wh per orbit) for 20% of the year. The worst part is the ~5-10% of the sun phases where we collect less than 0.5 Wh, which is the minimum necessary for the EPS to run without completely shutting down - those blackout periods seem to last for about 2 weeks straight. In 2 weeks the battery can freeze itself off pretty thoroughly to the point where the sat might not wake up afterwards…
As with Sc1, with an artificially confined attitude and almost no spin, we again notice resonance features in the histogram for 5.2, for example the twin peaks at 4.5 Wh and 5 Wh. It is interesting that despite the

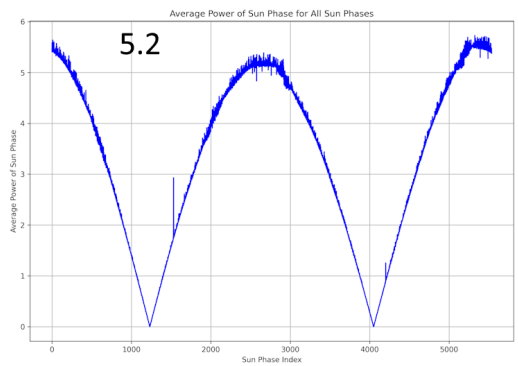
long downwards tail, the peaks of the histogram are higher than other scenarios - this makes sense since the sat consistently presents an entire long side flat towards the sun during good times.

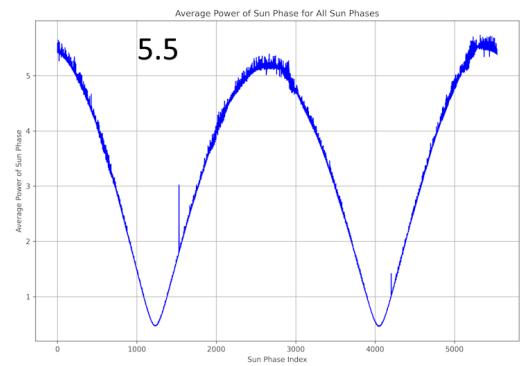


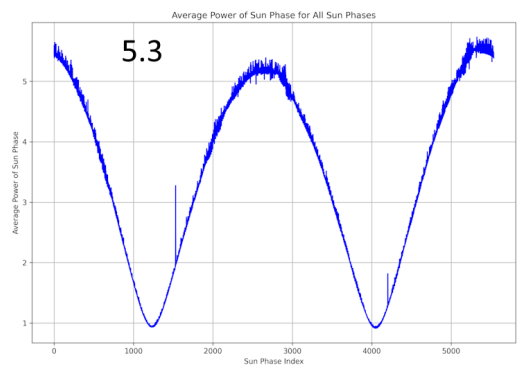


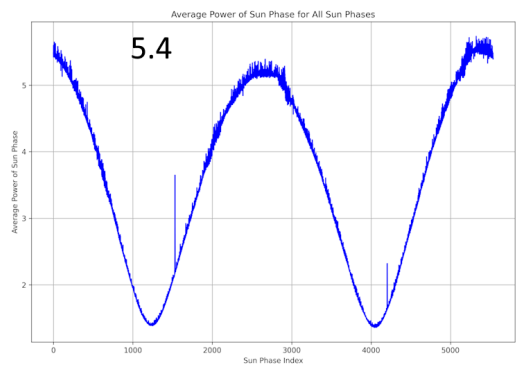












As expected, we see that lifting the sat's long axis off the ecliptic plane (scenarios 5.3-5.5) shifts the minimum energy upwards. For L2 (~1.4 Wh per orbit) we need at least 20 deg off the ecliptic but better even more. However, even 5 deg seems to almost be enough to limit the downside to 0.5 Wh per orbit and with 10 deg we shouldn't need to worry about battery damage (though we probably will incur significant OBC and radio downtime).

Conclusions

1) <u>Overall, the power budget closes, but with a very tight margin that is made uncertain due to thermal efficiency loss.</u> Not accounting for thermal losses, in tumbling and tidally locked scenarios we typically collect 3.5-4 Wh with a long-run average solar power of 2.5-3 W. This is about 15-25% higher than what we need to run the CRD (3 Wh per orbit or 2 W average consumption), which just about matches the worst-case thermal efficiency loss. Thus, the strong incentive to minimize power consumption remains.

2) <u>Sun phases are actually 60min long</u> and not 45min.

3) <u>We'll need to heavily modify our power distribution algorithm.</u> Our current algorithm relies on forecasting the instantaneous charging rate forward until the end of the sun phase. But we saw that with a not tidally-locked sat, unless spin rates are below 0.1 deg/sec, the sun phase instantaneous power bounces between 2-6 W many times per phase (and even below 0.1 deg/sec, the instantaneous charging rate is far from constant throughout the phase). With a tidally-locked sat, the profile has a consistent shape – roughly – but not one that's particularly easy to fit. Therefore, we'll want to shift to looking at power on an orbit scale rather than a 5 min scale, probably something like constraining total consumption over an orbit to the total harvest of the previous orbit's sun phase.

4) Seasonal variation is usually insignificant*. When the sat tumbles, it doesn't care about seasons*, and when it's tidally locked, there's a 20-25% bounce up and down together with monthly precession. This does mean that we can't use a single value for the expected harvest per sun phase, but we usually don't need to worry about it*. Except,

5) *: There is a danger zone. If a) the sat's spin axis is close to its long axis, and b) the sat's precession axis is close to the plane of the ecliptic, and c) the nutation angle is small, we're in for a lot of trouble. Power collection can fall as low as literally zero for up to a couple weeks, which, besides obviously shutting down the entire sat for that time, also presents a significant danger of the battery freezing out permanently. This is a small chance but big bad situation. The odds of our spin axis aligning with the sat's long axis at deployment are small, since all the deployment forces will be acting on the square face where they'll have a lot of leverage to tip the sat around an axis perpendicular to the long axis. Where we'll probably want to start worrying about this is towards the end of active detumbling but before the GGB tidally locks us. This makes it very important to get successive attitude measurements from the sat over the course of a few days right after active detumbling finishes. The sat's measurements of its own omega vector will give us the spin axis in the sat body frame, and by plotting multiple measurements of the sat's attitude (i.e. rotation matrix) we should be able to find its precession axis and nutation angle. The good news is that if we indeed end up in this situation, torquing away from it shouldn't be hard (at an angular acceleration of 0.15 deg/sec^2 (which is what we expect for the MTQs) we only need 16 sec to travel through 20 deg), as long as we can issue the command early enough.