Power System
&
Power Budget

Lawrence Reeves

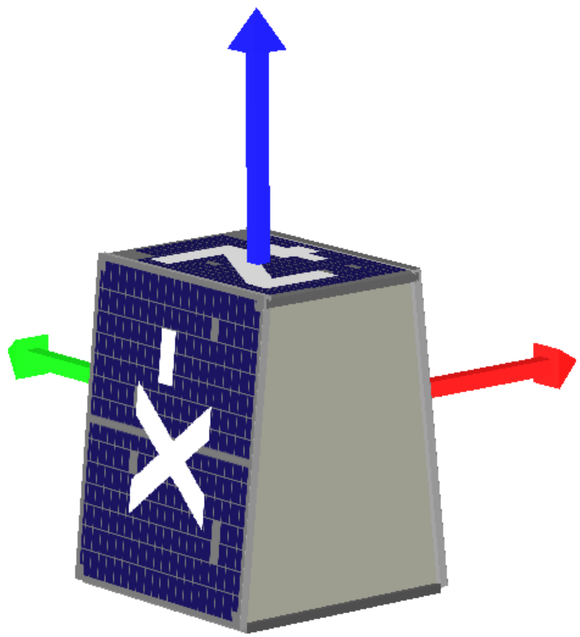
The objective of this presentation is to give a foundation of understanding of the power system and power budget of a satellite.

Power System Purpose

- Purpose: to provide enough power for the mission
  - Ensure power generated $\geq$ power consumed

- Be able to understand and account for:
  - Average power generation/consumption
  - Worst-case power generation/consumption
  - "Reasonable" operational power generation/usage scenario
  - Beginning-of-Life (BOL) versus End-of-Life (EOL)

Sample Mission Spacecraft



- Earth Observation / Science payloads.
- 400km altitude circular orbit. Orbit period = 92.6 minutes.
- 10:30 a.m. SSO LTAN.

- 1.0 m^2 solar panel on +X and –X faces.
- 0.5 m^2 solar panel on +Z face.

Power System Elements

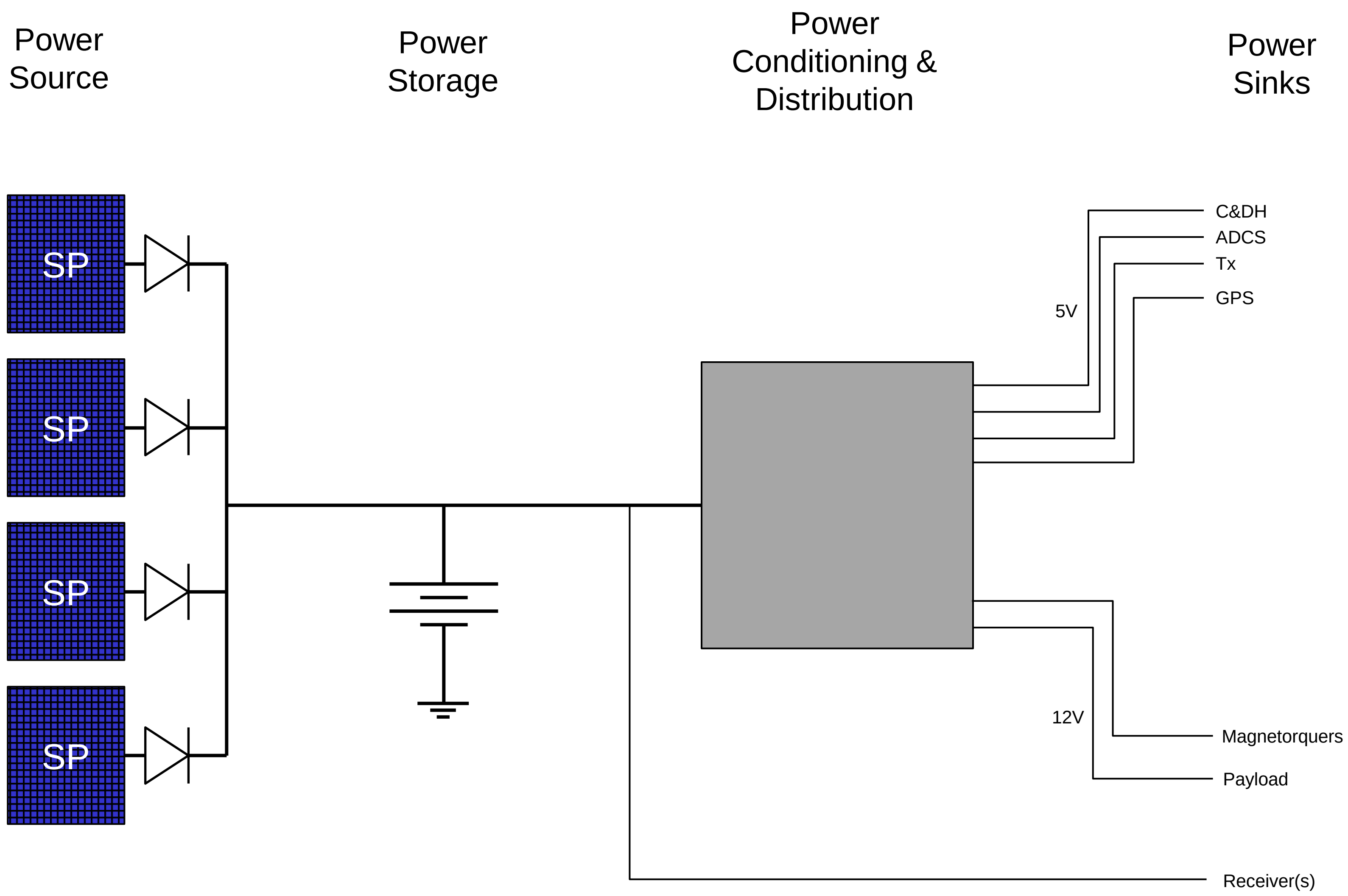
1. Power Source
   – Solar panels, Radioisotope Thermoelectric Generators (RTGs), Fuel Cells

2. Power Storage
   – Batteries

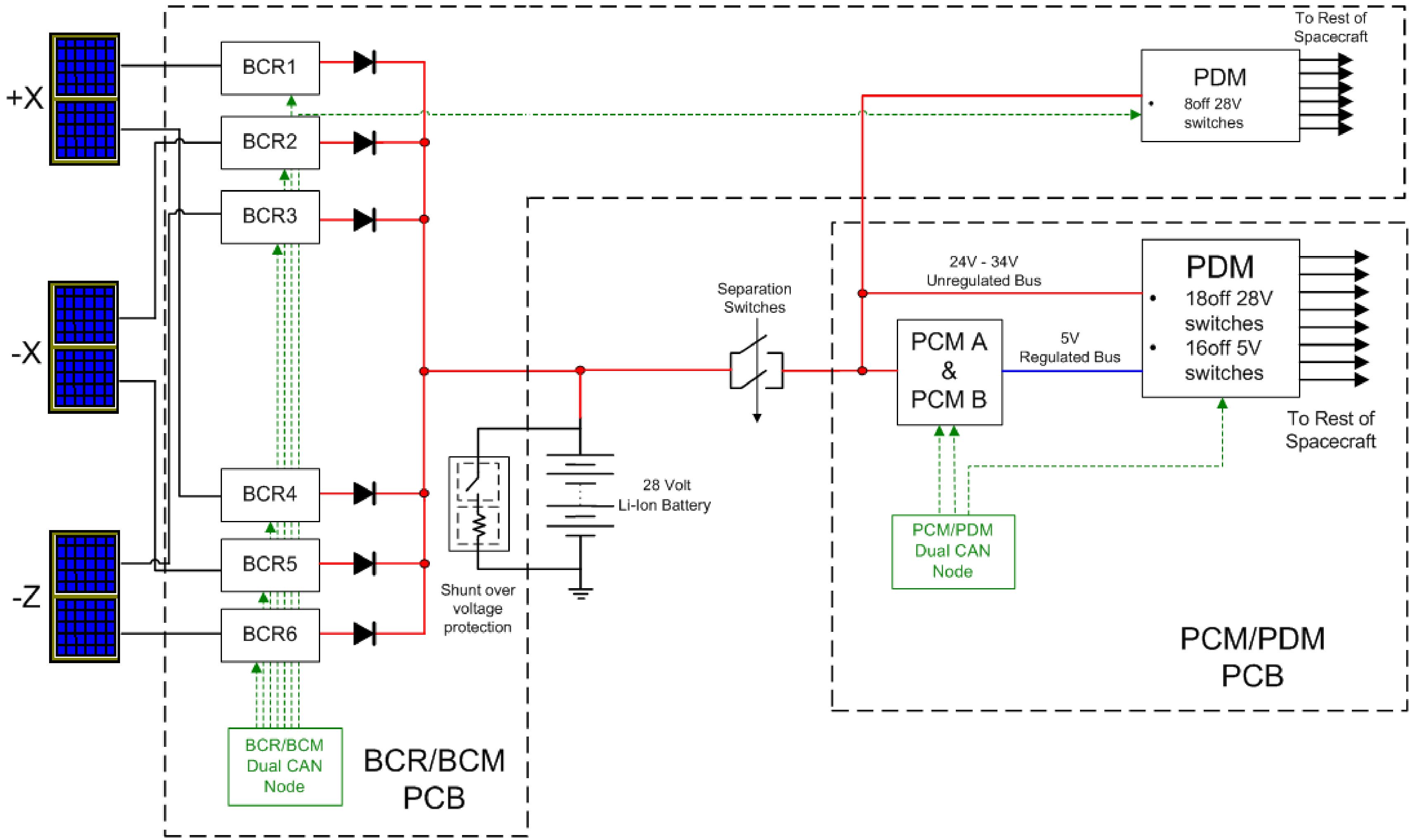
3. Power Conditioning & Distribution
   – Regulated power, power conversion (e.g., to 5V, 12V)
   – Be aware of the conversion efficiencies!

4. Power sink(s)
   – i.e., components that .use power

Basic Power System Architecture



RapidEye Power System Architecture



18/04/05

POWER CONSUMPTION

Basic Power Budget – Average Orbit

Component	Power Usage (W)	Duty Cycle	Orbit Average Power (W)
Power Control Module	9.0	100.0%	9.0
Main CPU (C&DH)	12.0	100.0%	12.0
AD&C Cpmpuer	1.5	100.0%	1.5
- Reaction Wheels	7.0	100.0%	7.0
- Star Tracker	3.0	100.0%	3.0
- GPS	6.0	100.0%	6.0
- Magnetometer	1.0	100.0%	1.0
- Magnetorquer	4.0	6.7%	0.3
Receiver 1	2.0	100.0%	2.0
Receiver 2	2.0	0.0%	0.0
Transmitter 1	5.0	3.7%	0.2
Transmitter 2	5.0	0.0%	0.0
Payload 1	15.0	30.0%	4.5
Payload 2	35.0	10.0%	3.5
Total			50.0

Basic Power Budget – Worst-case orbit

Component	Power Usage (W)	Duty Cycle	Orbit Average Power (W)
Power Control Module	9.0	100.0%	9.0
Main CPU (C&DH)	12.0	100.0%	12.0
AD&C Cpmpuer	1.5	100.0%	1.5
- Reaction Wheels	7.0	100.0%	7.0
- Star Tracker	3.0	100.0%	3.0
- GPS	6.0	100.0%	6.0
- Magnetometer	1.0	100.0%	1.0
- Magnetorquer	4.0	50.0%	2.0
Receiver 1	2.0	100.0%	2.0
Receiver 2	2.0	0.0%	0.0
Transmitter 1	5.0	12.0%	0.6
Transmitter 2	5.0	0.0%	0.0
Payload 1	15.0	40.0%	6.0
Payload 2	35.0	25.0%	8.8
Total			58.9

Basic Power Budget – Some Issues

- Where did you get the unit power usage values from?
  - Estimate for a new design? Spec Sheet? Measured values in a realistic usage setting?
  - For each of those, you will want to add in some margin.

- If the Power System is converting voltage, there is an efficiency loss. E.g., on RapidEye, the 28V-to-12V converter was only 67% efficient. That means that every Watt needed by a 12V unit requires 1.5W of power at 28V (the "source" power).

New Power Budget – Average Orbit

Component	Power Usage (W)	Duty Cycle	Orbit Average Power (W)	Source?	Margin	Power Usage with Margin	Orbit Average Power (W)	Voltage	Efficiency Factor	Orbit Average Power (W)
Power Control Module	9.0	100.0%	9.0	Spec sheet	5.0%	9.5	9.5	12	98%	9.6
Main CPU (C&DH)	12.0	100.0%	12.0	Measured	2.0%	12.2	12.2	5	66%	18.5
AD&C Cpmpuer	1.5	100.0%	1.5	Spec sheet	2.0%	1.5	1.5	5	66%	2.3
- Reaction Wheels	7.0	100.0%	7.0	Alteration	15.0%	8.1	8.1	12	98%	8.2
- Star Tracker	3.0	100.0%	3.0	Spec sheet	5.0%	3.2	3.2	5	66%	4.8
- GPS	6.0	100.0%	6.0	Measured	2.0%	6.1	6.1	5	66%	9.3
- Magnetometer	1.0	100.0%	1.0	Measured	2.0%	1.0	1.0	5	66%	1.5
- Magnetorquer	4.0	6.7%	0.3	Measured	2.0%	4.1	0.3	12	98%	0.3
						0.0	0.0			
Receiver 1	2.0	100.0%	2.0	Measured	2.0%	2.0	2.0	12	98%	2.1
Receiver 2	2.0	0.0%	0.0	Measured	2.0%	2.0	0.0	12	98%	0.0
Transmitter 1	5.0	3.7%	0.2	Measured	2.0%	5.1	0.2	12	98%	0.2
Transmitter 2	5.0	0.0%	0.0	Measured	2.0%	5.1	0.0	12	98%	0.0
						0.0	0.0			
Payload 1	15.0	30.0%	4.5	Alteration	15.0%	17.3	5.2	12	98.0%	5.3
Payload 2	35.0	10.0%	3.5	New Design	25.0%	43.8	4.4	12	98.0%	4.5
Total			50.0				53.6			66.6

New Power Budget – Worst-case orbit

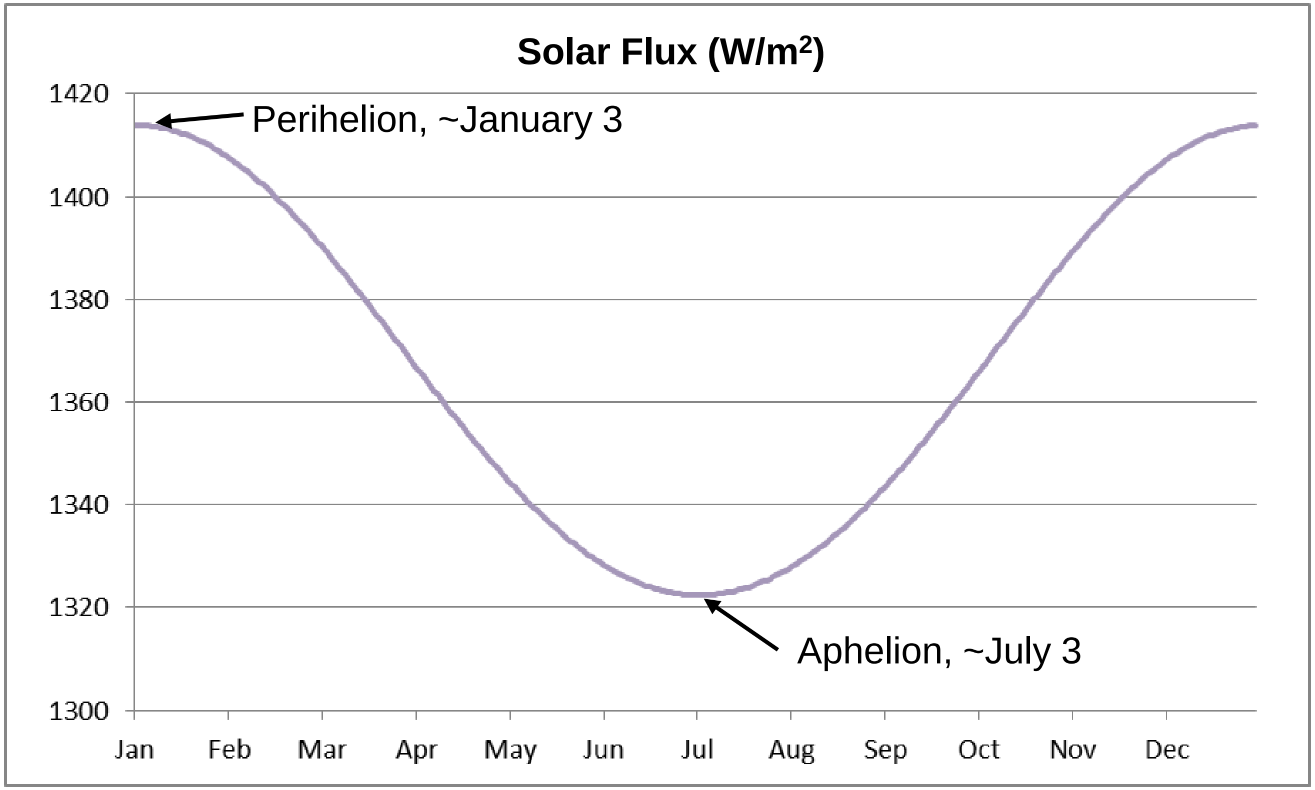
Component	Power Usage (W)	Duty Cycle	Orbit Average Power (W)	Source?	Margin	Power Usage with Margin	Orbit Average Power (W)	Voltage	Efficiency Factor	Orbit Average Power (W)
Power Control Module	9.0	100.0%	9.0	Spec sheet	5.0%	9.5	9.5	12	98%	9.6
Main CPU (C&DH)	12.0	100.0%	12.0	Measured	2.0%	12.2	12.2	5	66%	18.5
AD&C Cpmpuer	1.5	100.0%	1.5	Spec sheet	2.0%	1.5	1.5	5	66%	2.3
- Reaction Wheels	7.0	100.0%	7.0	Alteration	15.0%	8.1	8.1	12	98%	8.2
- Star Tracker	3.0	100.0%	3.0	Spec sheet	5.0%	3.2	3.2	5	66%	4.8
- GPS	6.0	100.0%	6.0	Measured	2.0%	6.1	6.1	5	66%	9.3
- Magnetometer	1.0	100.0%	1.0	Measured	2.0%	1.0	1.0	5	66%	1.5
- Magnetorquer	4.0	50.0%	2.0	Measured	2.0%	4.1	2.0	12	98%	2.1
						0.0	0.0			
Receiver 1	2.0	100.0%	2.0	Measured	2.0%	2.0	2.0	12	98%	2.1
Receiver 2	2.0	0.0%	0.0	Measured	2.0%	2.0	0.0	12	98%	0.0
Transmitter 1	5.0	12.0%	0.6	Measured	2.0%	5.1	0.6	12	98%	0.6
Transmitter 2	5.0	0.0%	0.0	Measured	2.0%	5.1	0.0	12	98%	0.0
						0.0	0.0			
Payload 1	15.0	40.0%	6.0	Alteration	15.0%	17.3	6.9	12	98.0%	7.0
Payload 2	35.0	25.0%	8.8	New Design	25.0%	43.8	10.9	12	98.0%	11.2
Total			58.9				64.1			77.3

POWER GENERATION

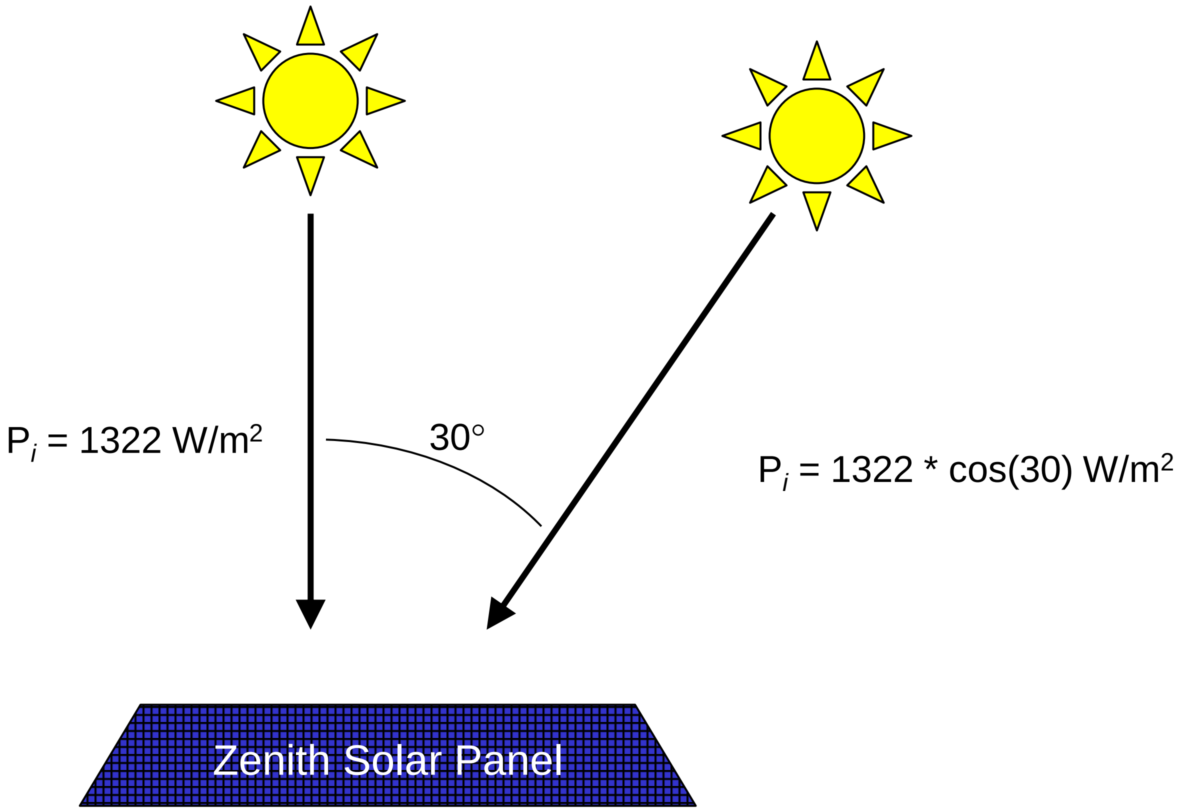
This section assumes we're using Solar Panels for a LEO orbit.

Annual Variation of Solar Flux

The Earth's orbit around the Sun is not perfectly circular, it is elliptical. Its distance from the Sun varies throughout the year (orbit) by about 1.7%, which causes a ~3.3% variation in the Solar Flux received at Earth, between ~1322 W/m^2 and 1414 W/m^2, with the average being 1368 W/m^2.



Solar Power Incident at Aphelion

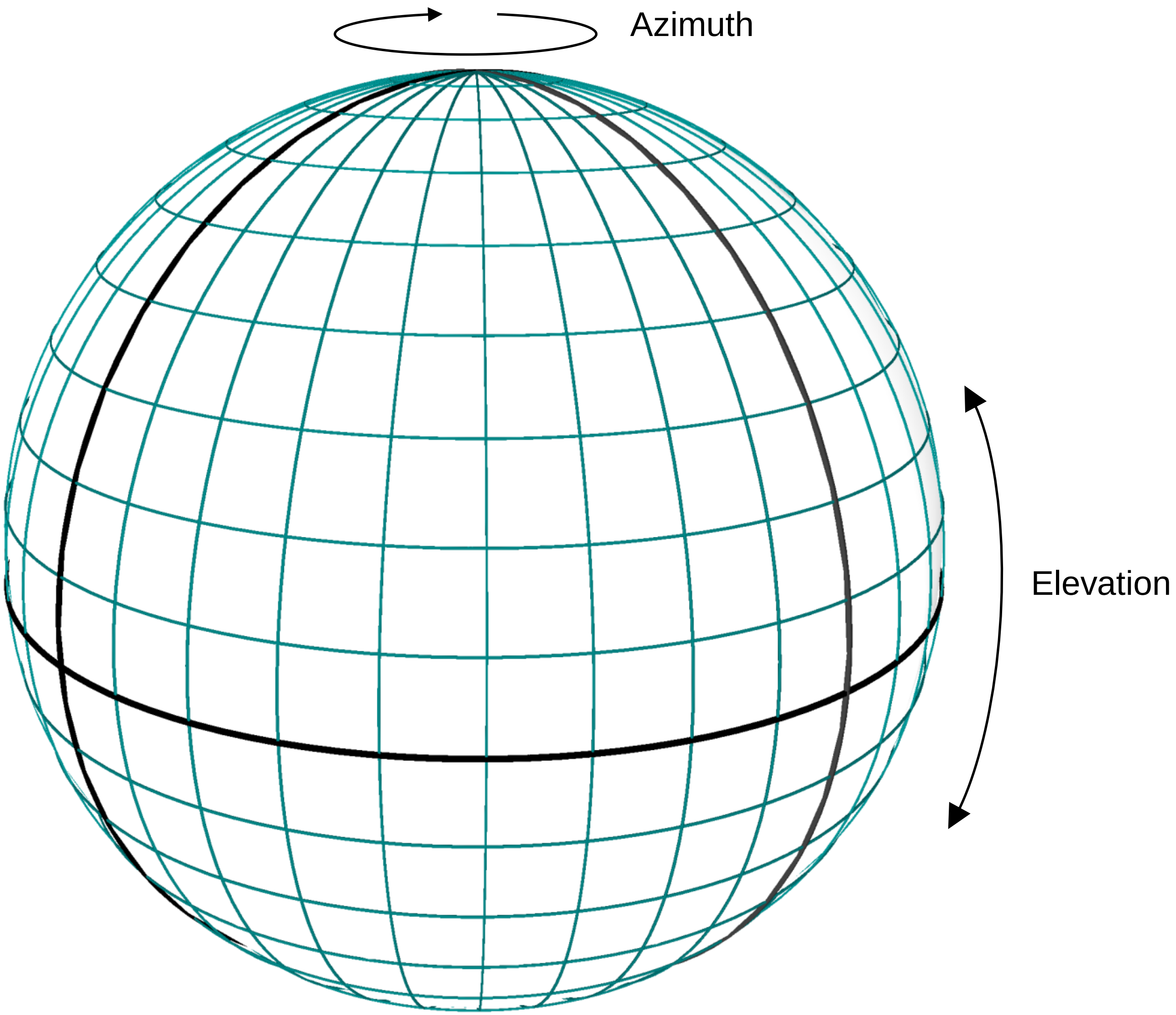


Peak Solar Panel Power Output = P_i * SP Area * SP Efficiency

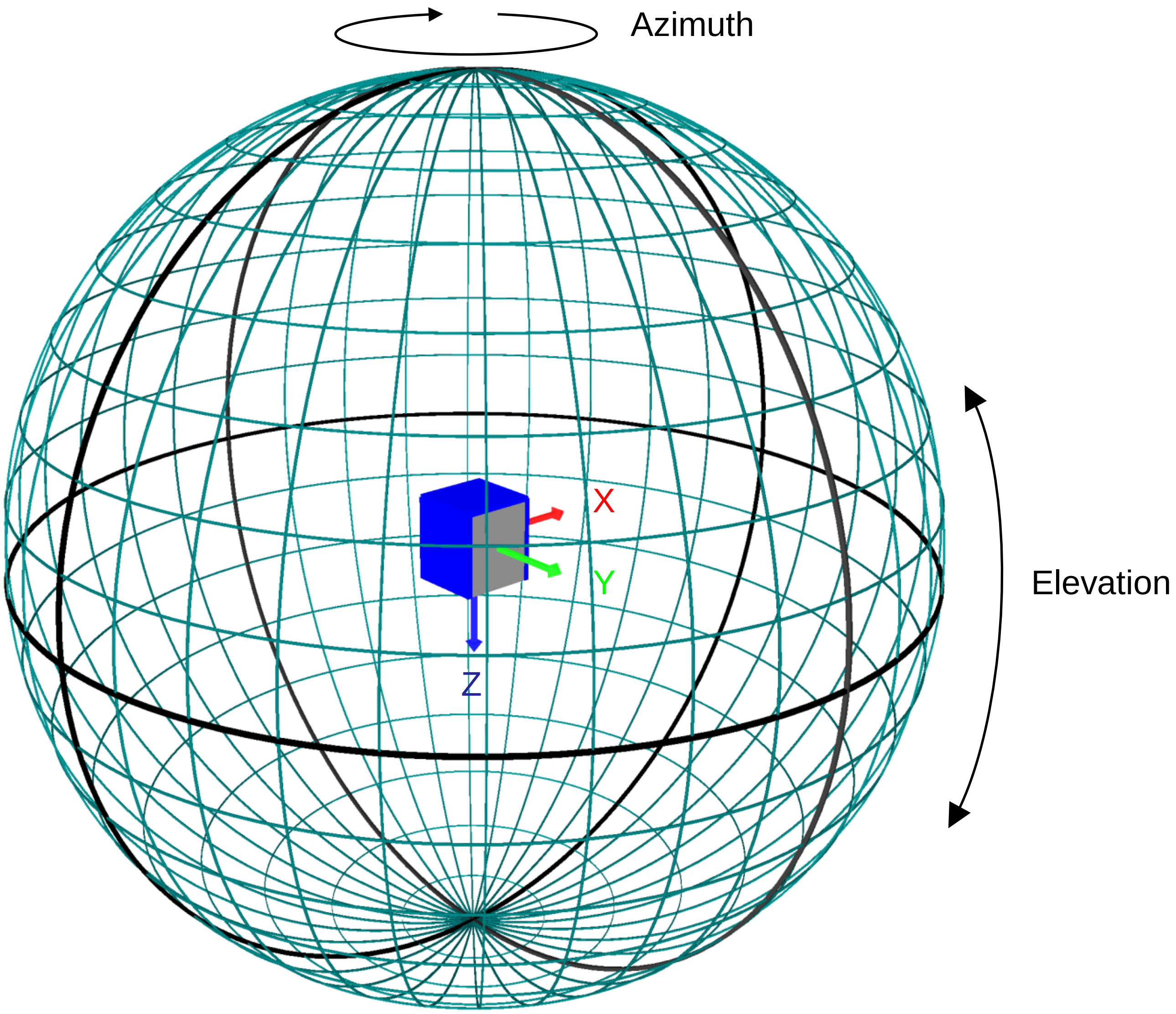
= 1322 * 0.5 * 17% = 112.3W

SOME ORBIT STUFF

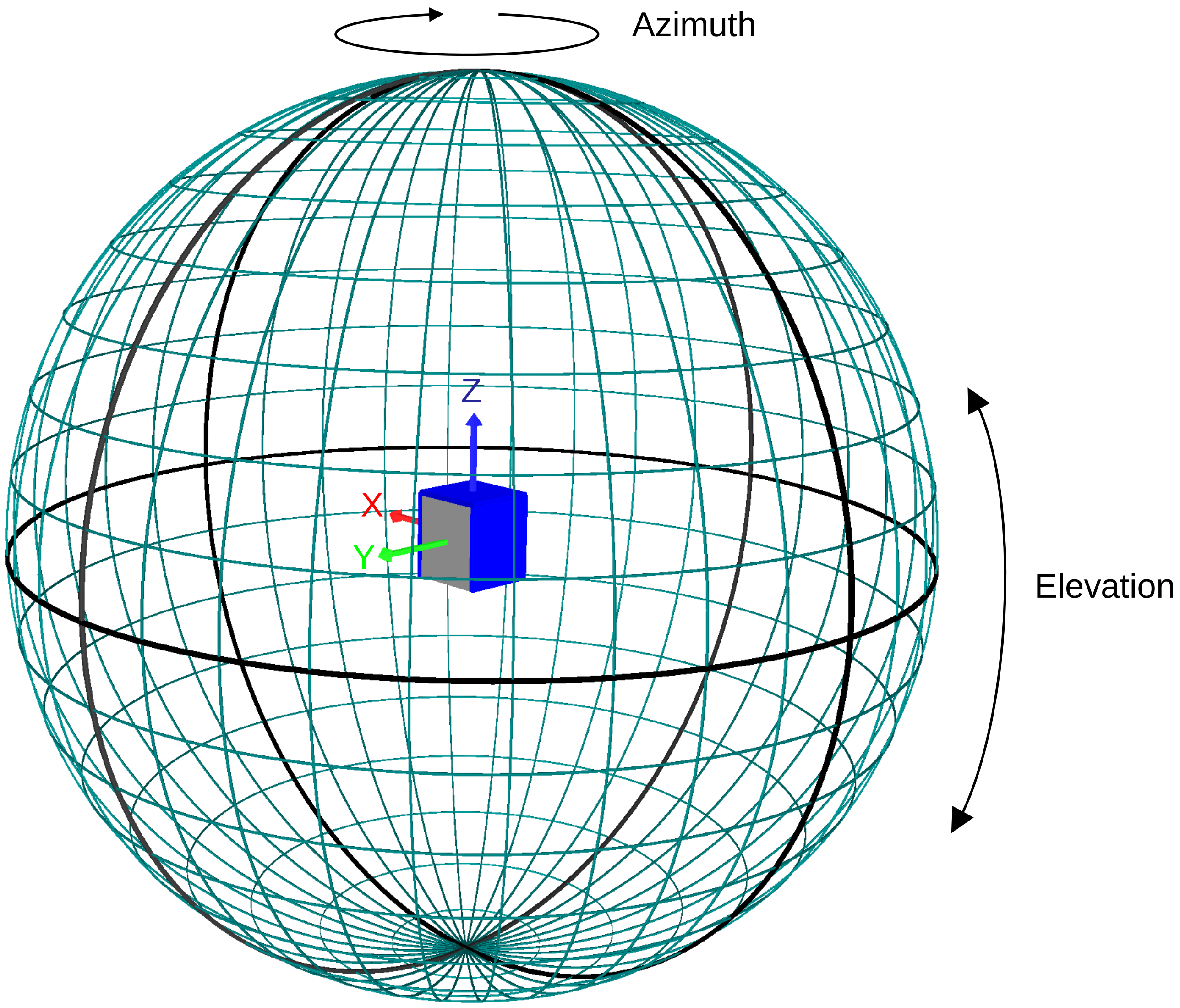
An Attitude Sphere for a Satellite



Attitude Sphere



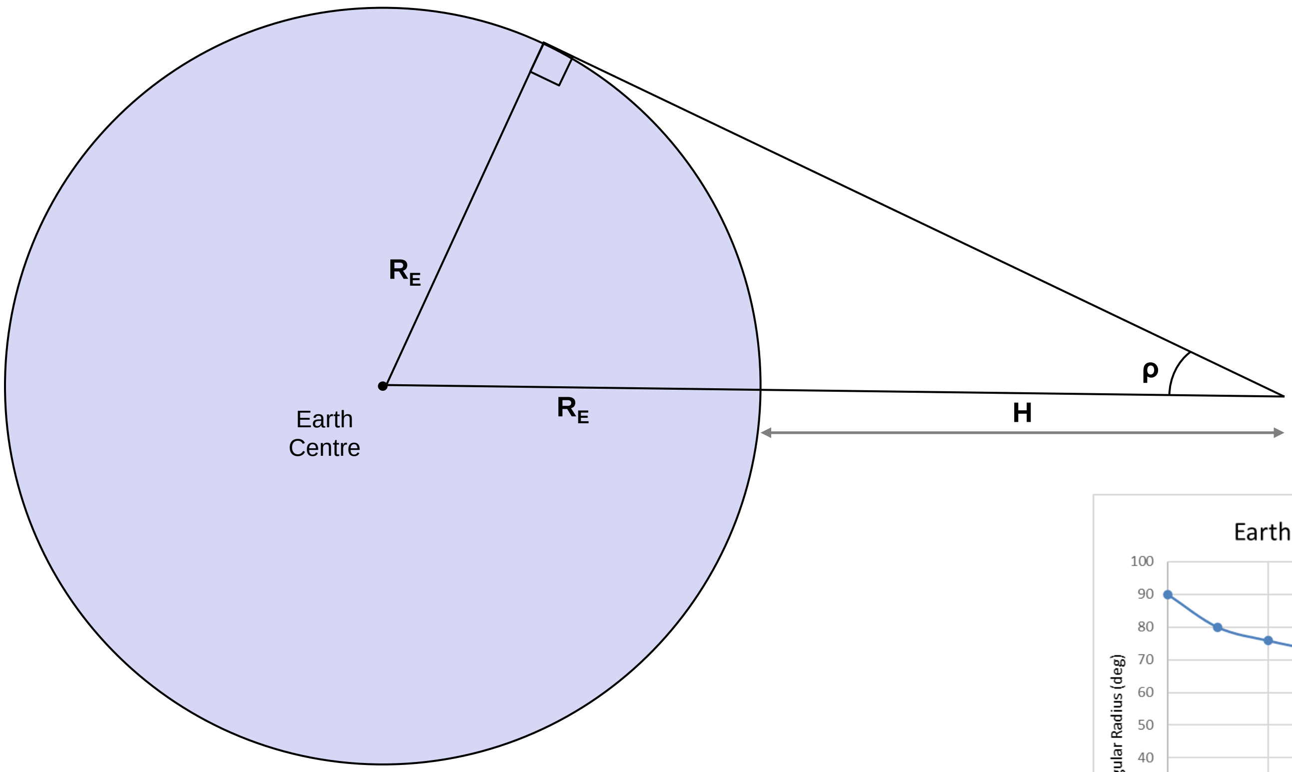
Attitude Sphere (my preference)

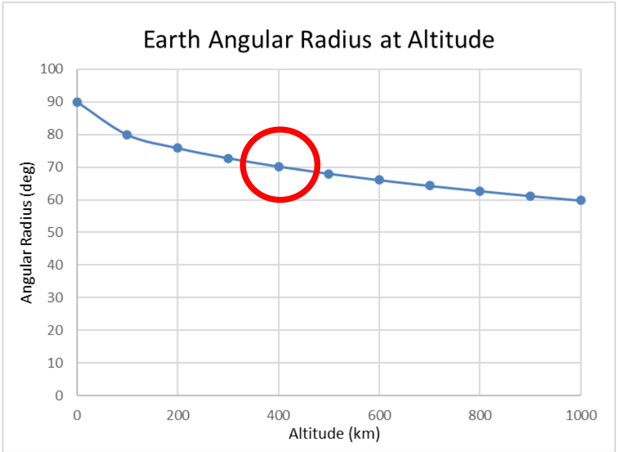


Earth's Angular Radius

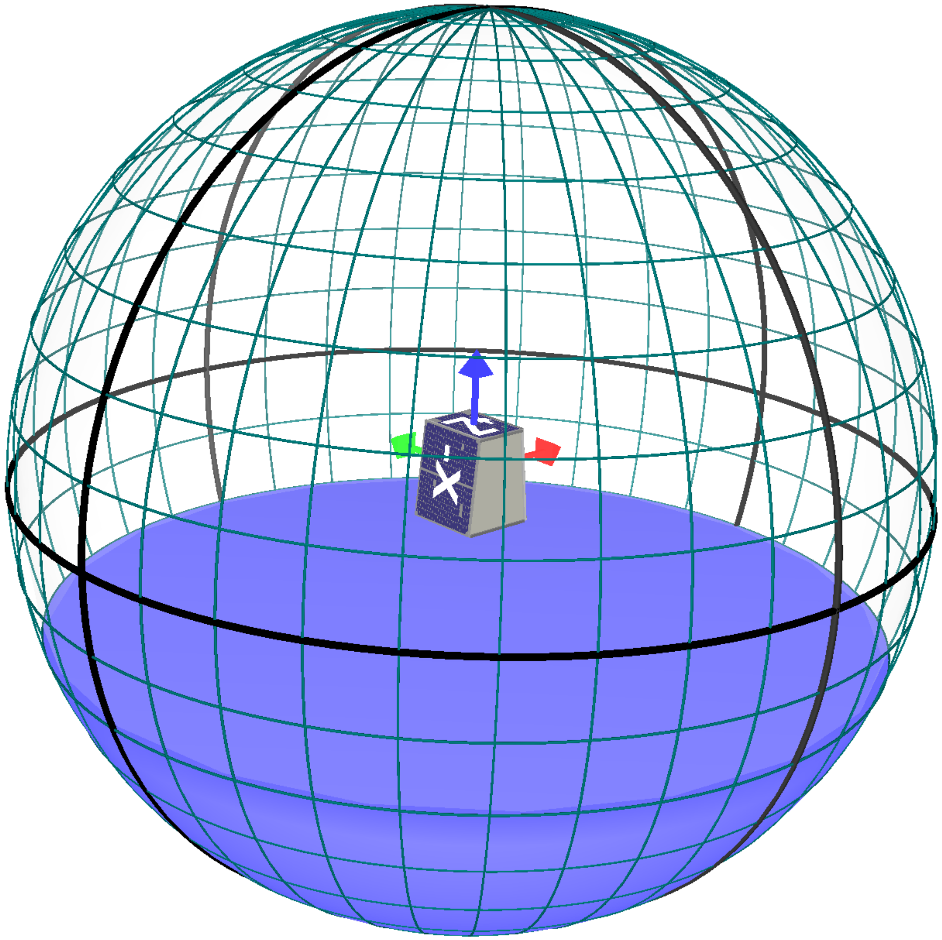
At a given altitude (height) H, the angular radius ρ of the Earth is:

$$\rho = \sin^{-1}(R_E / (R_E + H))$$



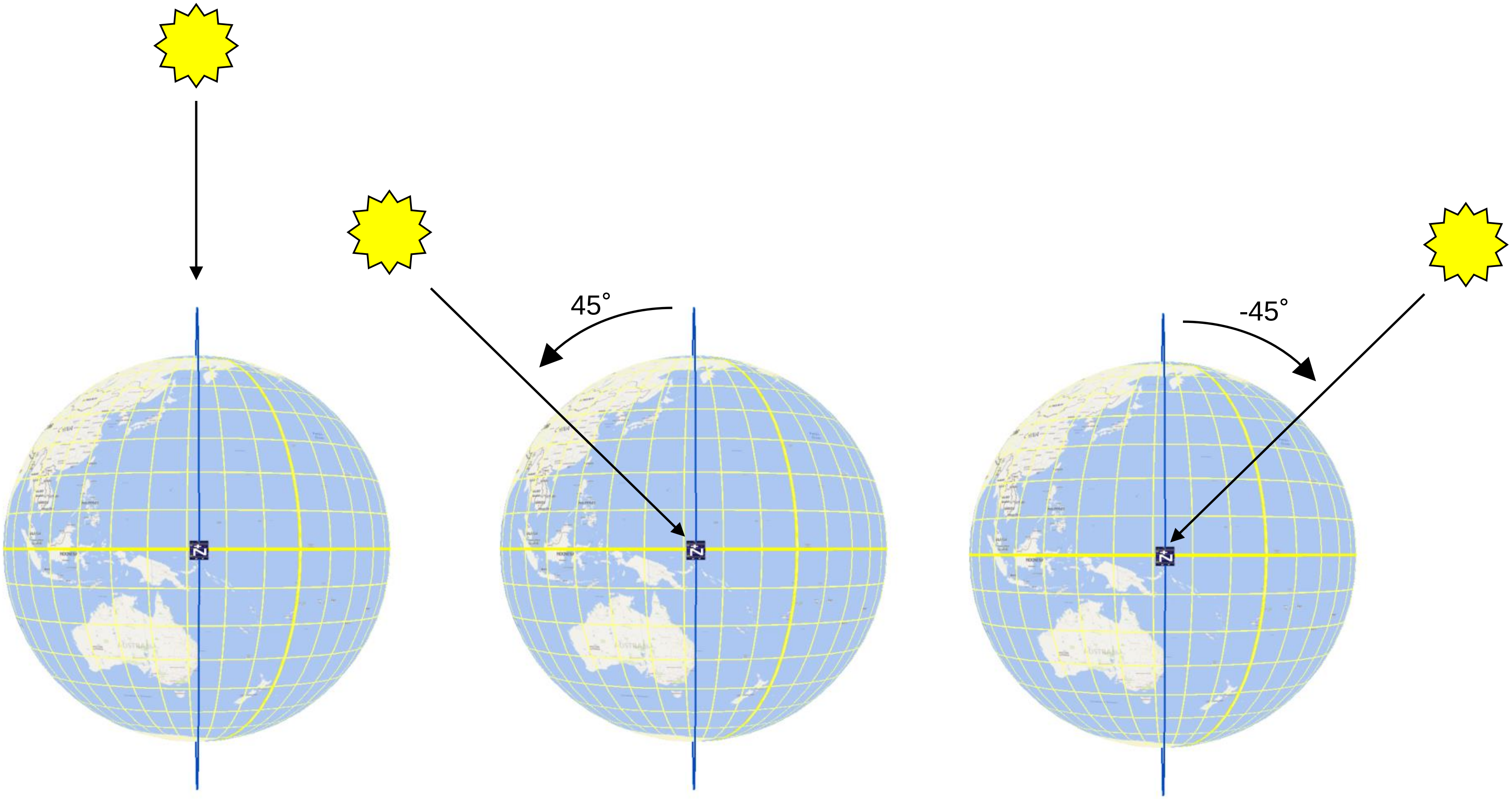


Earth's Angular Radius



Beta Angle

The Beta Angle is the angle between the sun and the orbit plane

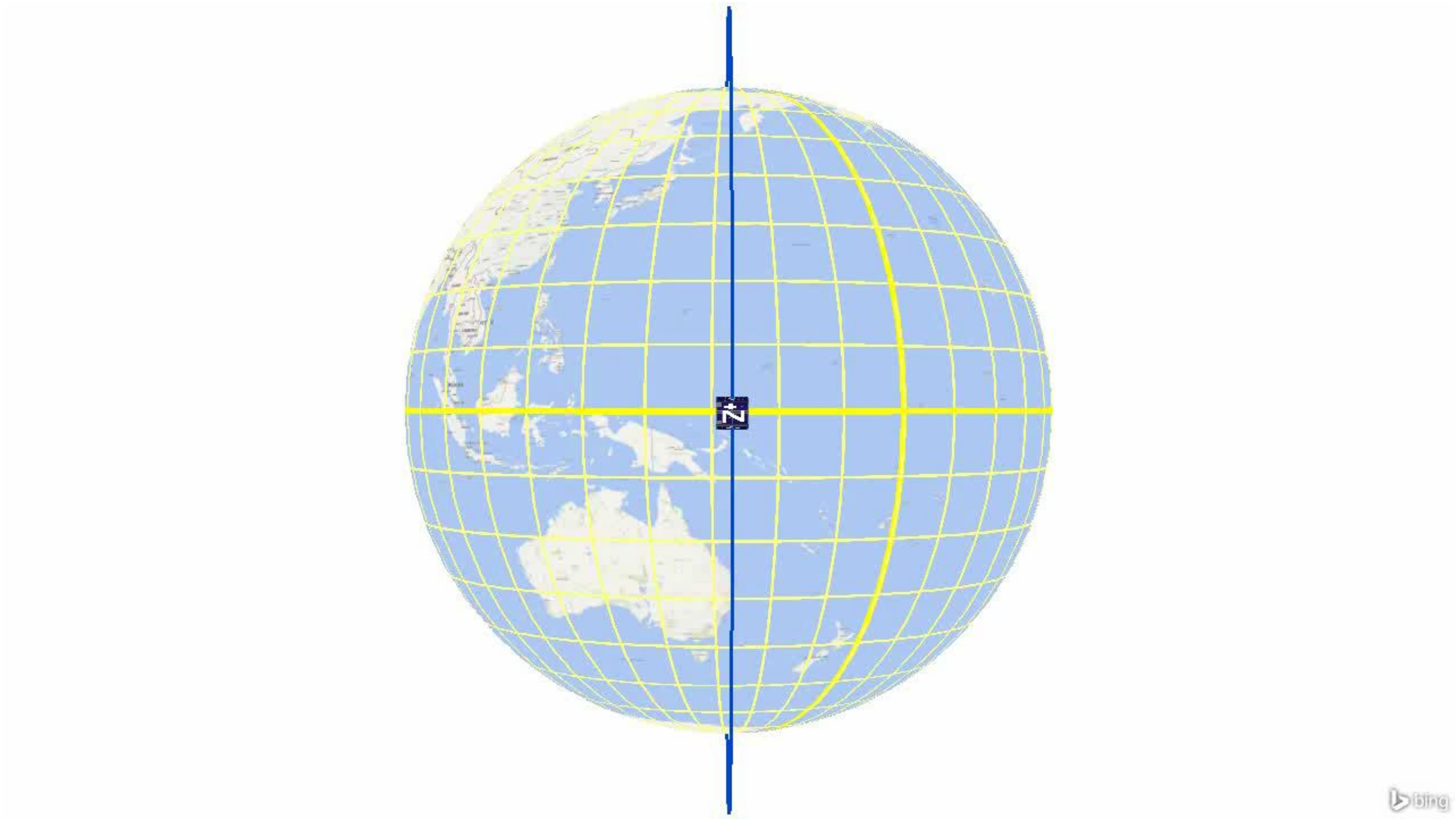


0° Beta Angle

+45° Beta Angle

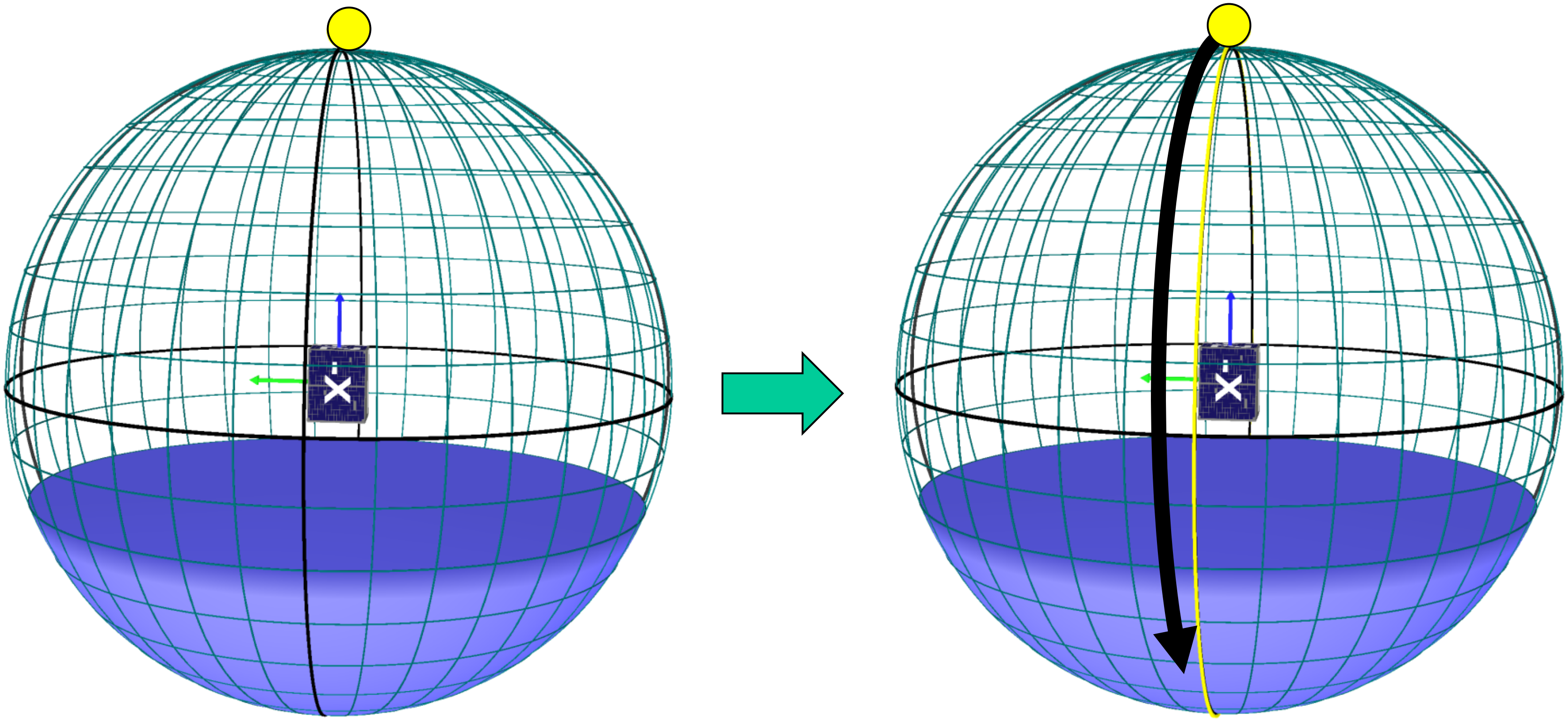
-45° Beta Angle

Looking from the Sun to a Satellite in Orbit



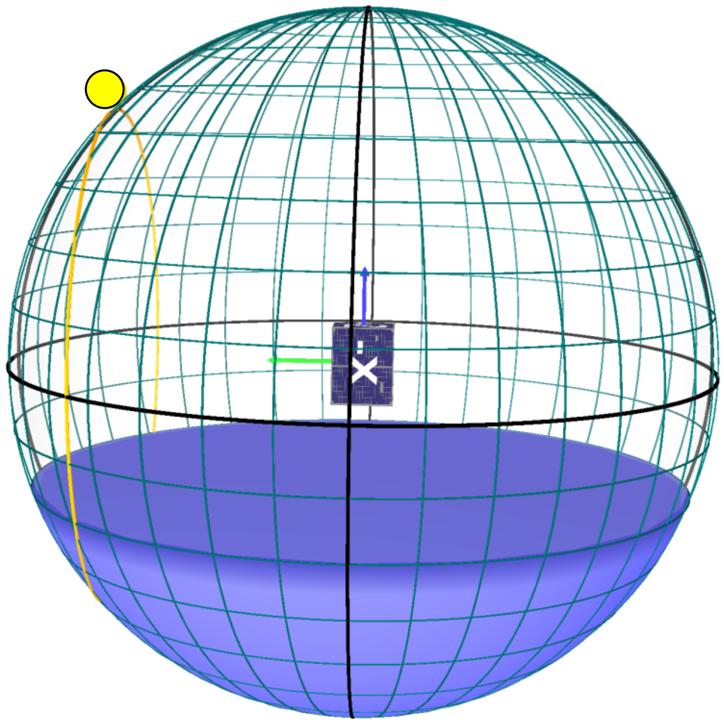
0° Beta Angle (a "noon-midnight" orbit).

Sun Movement from the Spacecraft Perspective

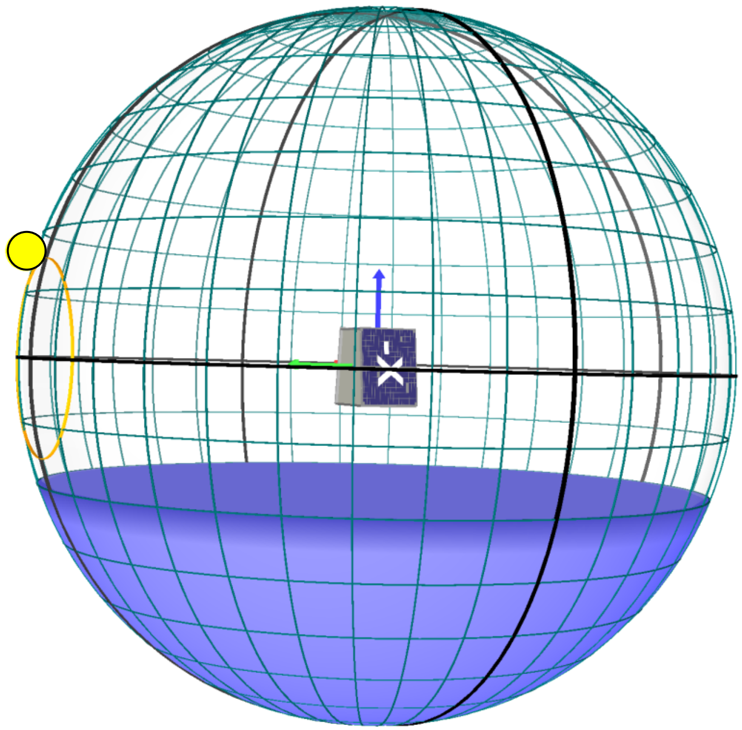


0˚ Beta Angle (a "noon-midnight" orbit)

Sun Movement from the Spacecraft Perspective



45° Beta Angle



75° Beta Angle

When the Beta angle is greater than the Earth's angular radius, the spacecraft is illuminated by the sun throughout the orbit.

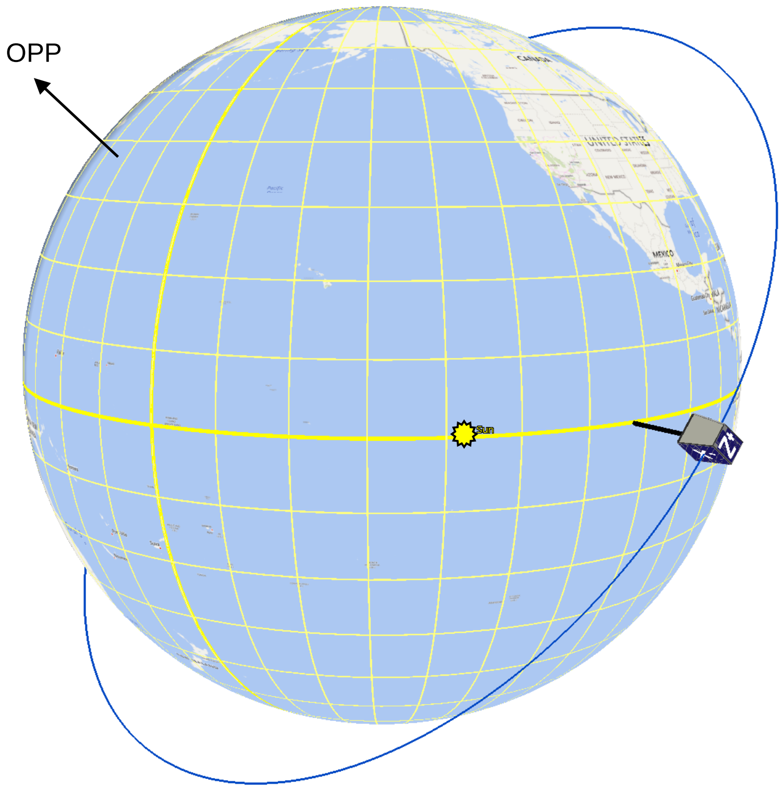
Calculating the Beta Angle (β)

1. Find the latitude & longitude of the "Pole" of the orbit plane – the vector from the centre of the Earth going perpendicular to the orbit plane (using right-hand rule) – at an Ascending Node (where the satellite crosses the Equator going north):
   - OPP_{Lat} = 90° minus the orbit inclination
   - OPP_{Long} = longitude of the Ascending Node minus 90°

2. Find the Latitude & Longitude of the Sub-Solar Point (the point on the Earth where the sun is directly overhead):
   - SSP_{Lat}
   - SSP_{Long}

3. The Beta Angle is 90° minus the angle between SSP & OPP.

Example for a 52° Inclination Orbit



OPP_{Lat} = (90° - 52°) = 38°
OPP_{Long} = (-112° - 90°) = -202° = 158°

SSP_{Lat} = 0°
SSP_{Long} = -138

Angle between = 69.8°

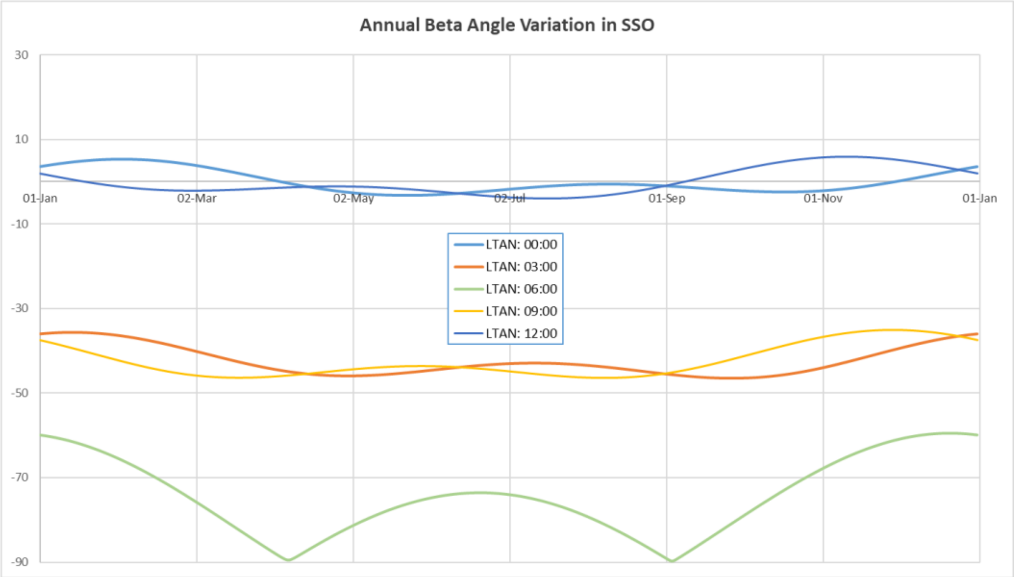
Beta Angle = (90° - Angle between) = 20.2°

What is the Maximum/Minimum Beta Angle?

- For prograde orbits with an inclination between 0° and 66.55°:
  - (-inclination – 23.45°) ≤ β ≤ (inclination + 23.45°)

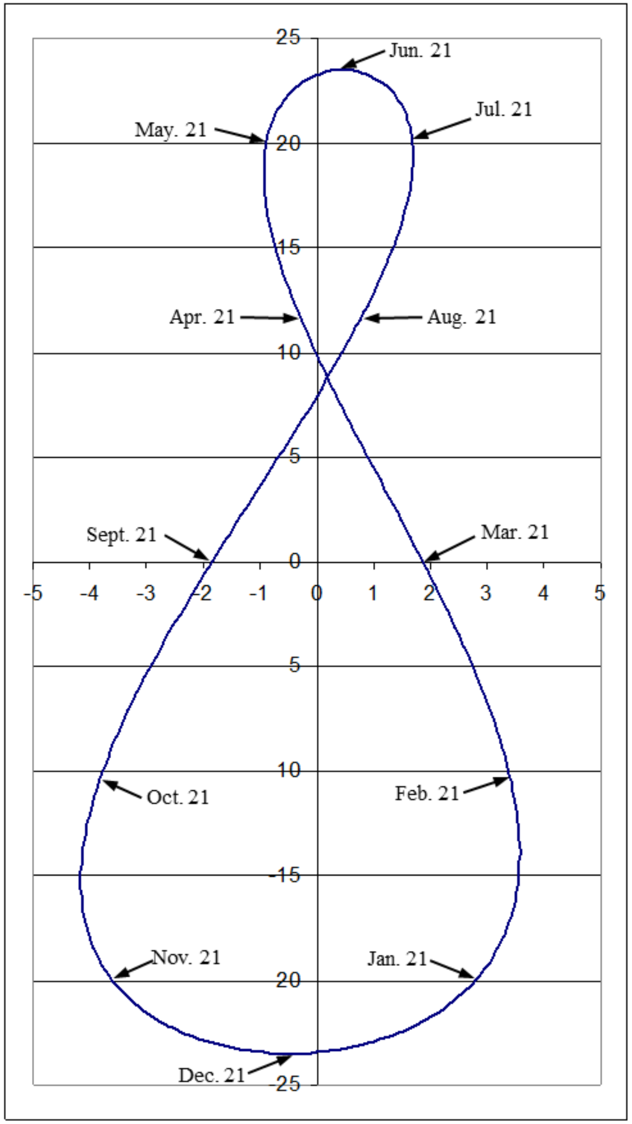
- For orbits with an inclination between 66.55° and sun-synchronous:
  - -90° ≤ β ≤ 90°

- For sun-synchronous orbits:
  - It depends on the LTAN (Local Time of the Ascending Node)



Sun Position During the Year - Analemma

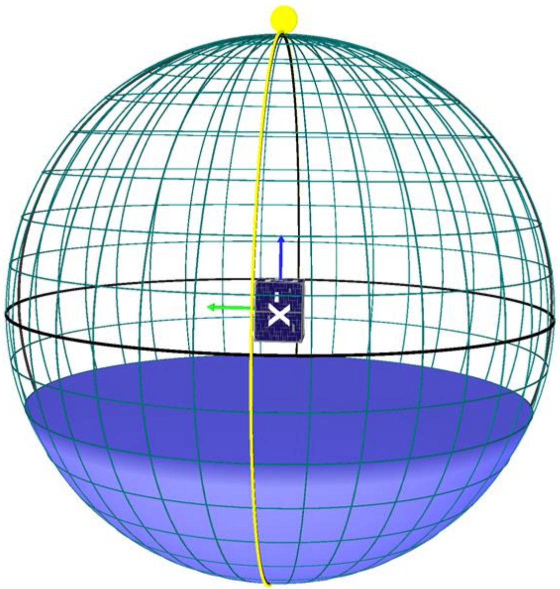
- The analemma is the path which the sun's sub-solar point follows over the course of a year.
- The analemma can significantly affect the Beta Angle, depending on the orbit.



What is the Eclipse Fraction?

In the 0° Beta Angle case ("noon-midnight" orbit), the eclipse fraction is simple to calculate (for a circular orbit):

- ρ = the angular radius of the Earth
- 2*ρ = the angular diameter of the Earth –the portion which the sun spends in eclipse
- The eclipse fraction = 2*ρ / 360°
- The eclipse duration = (2*ρ / 360°) * the orbit period



In a 400km circular orbit:

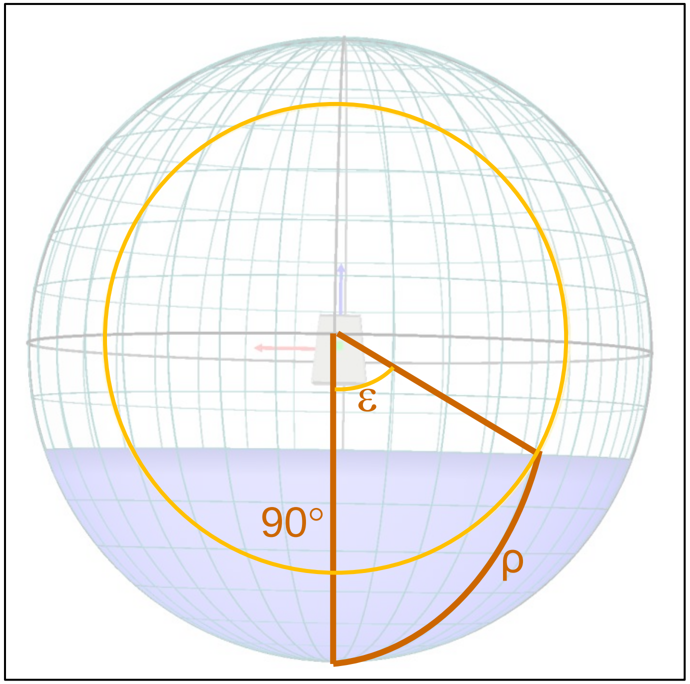
- ρ = 70.2°
- Eclipse Angle ε = 2*ρ = 140.4°
- Eclipse fraction = (ε / 360°) = (140.4° / 360°) = 39%

- At 400km, the orbit period is 92.6 minutes

- => the eclipse duration is 39% of 92.6 = 36.1 minutes

Eclipse Fraction: $\beta \neq 0$?

When the Beta Angle is not 0° (e.g., 45°) :



Given:

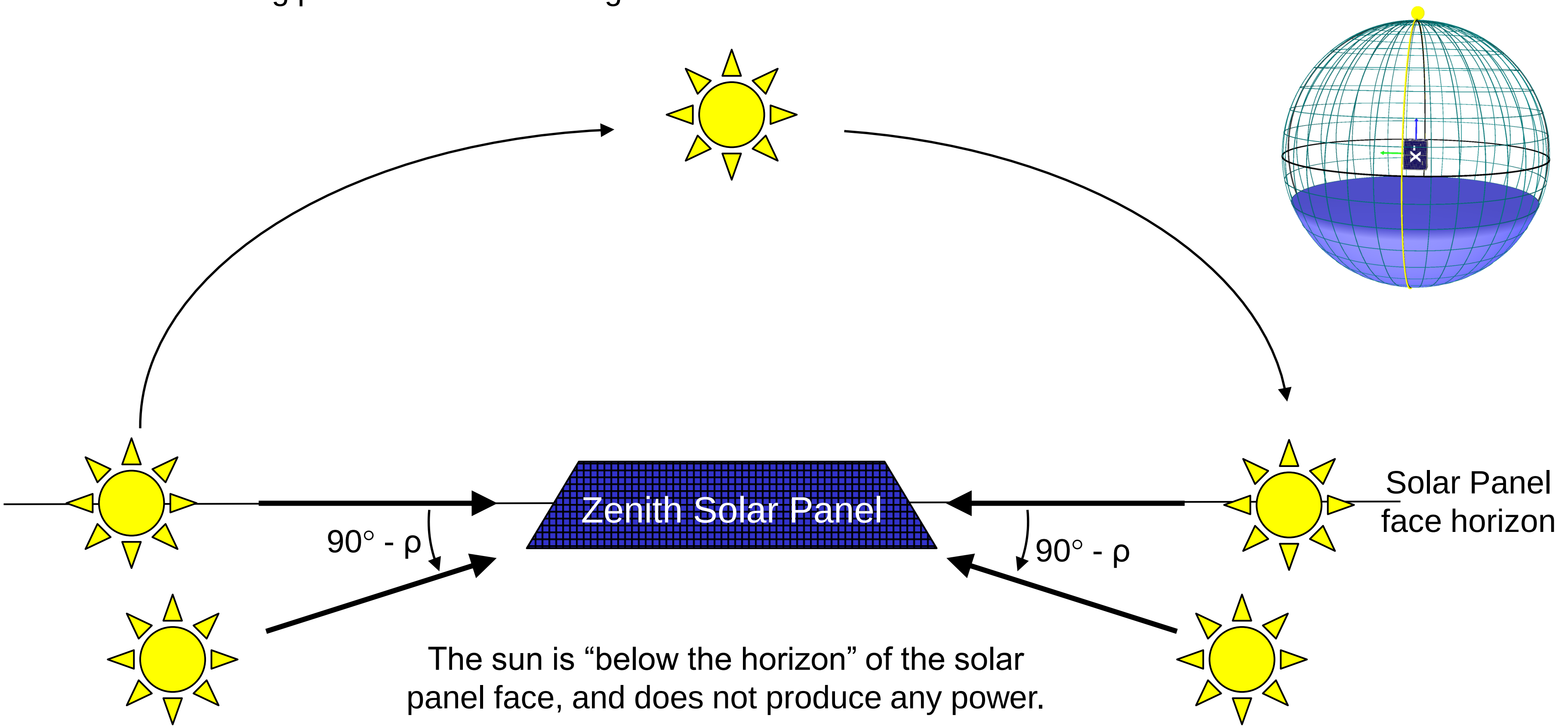
- ρ = 70.2°
- β = 45°
- Eclipse angle ε = 2*cos^{-1}(cos(ρ) / sin(90-β))
  = 122.8°

- Eclipse fraction = 122.8° / 360° = 34.1%

- Eclipse duration = 34.1% of 92.6 = 31.6 minutes

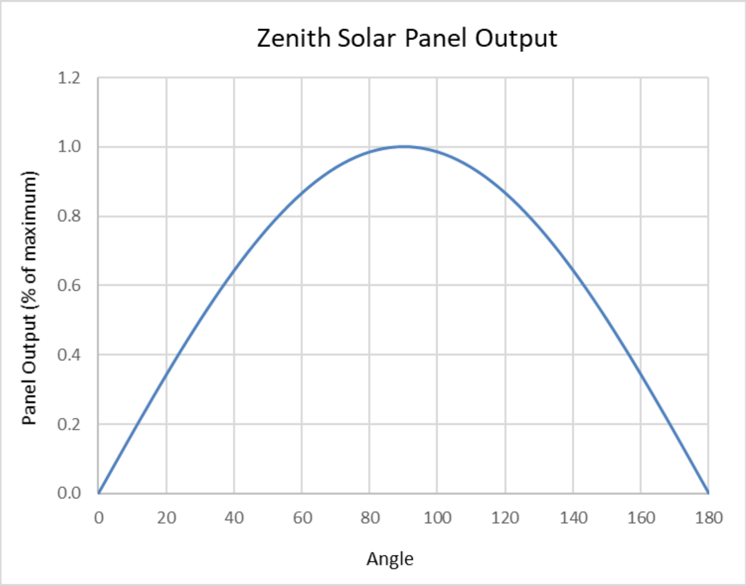
Zenith Solar Panel Illumination Profile: $\beta = 0°$

For a Zenith-facing panel in a noon-midnight orbit:



What does the power output profile of the Solar Panel look like?

Zenith Solar Panel Power Output: $\beta = 0°$



What is the total output power of this Panel?

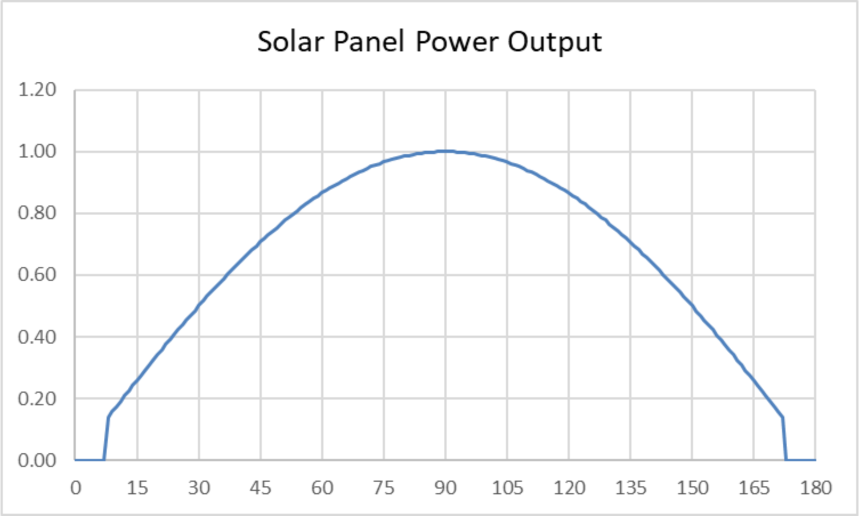
- The average value of sin from 0 to 180 degrees is ~0.63 (i.e., 63% of the Peak Power output)

- From our satellite, the Zenith panel Peak Power output = 112.3W
- This panel is generating power for 50% of the orbit, so the "Orbit Average Power" will be:
  - 112.3W * 0.63 * 0.5 = 35.7W.

However…

On RapidEye, we assumed the solar cells would only produce power if the sun angle was at least 8° above the panel's face horizon. *

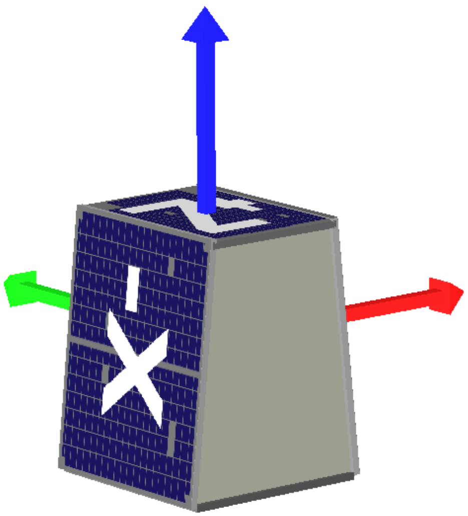
So, the power generation curve will look like:



If using this constraint, the power output only drops by 0.3W, to 35.4W.

* I have not been able to find out whether this was simply a bit of extra margin (since the power output between 0 and 8 degrees is minimal anyway), or whether there was a physical limitation on how low the sun angle could be and still register power. Having a bit of margin is not a bad thing. I mean, if your power budget is so stressed that 0.3W makes a big difference, you've probably got other issues .

For Our Mission

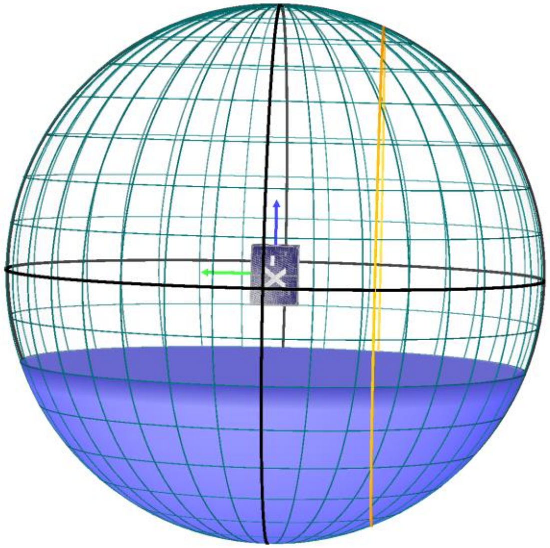


- 1.0 m^2 solar panel on +X and –X faces, 17% efficiency cells.
  - At Aphelion, maximum panel output = 1322 W/m^2 * 1.0 m^2 * 17% = 224 W
  - Orbit Average Power = 0.63 * 50% * 224W = 70.7 W

- 0.5 m^2 solar panel on +Z face, 17% efficiency cells.
  - At Aphelion, maximum panel output = 1322 W/m^2 * 0.5 W/m^2 * 17% = 112 W
  - Orbit Average Power = 0.63 * 50% * 224W = 35.4 W

Zenith Panel Output – β = -22.5°

For a Zenith-facing panel with a Beta Angle of -22.5° (this corresponds to a 10:30 a.m. LTAN, which is common for earth observation satellites in sun-synchronous orbits).



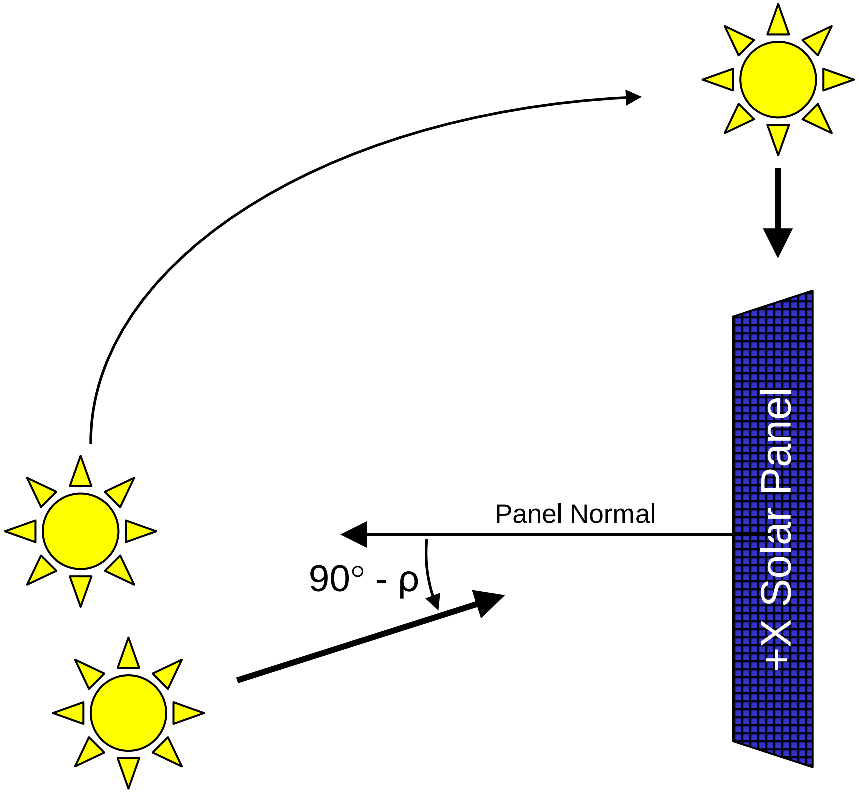
The illumination profile is identical to the β = 90° case, except that the sun is rotated from the panel normal by β = -22.5°. So, the power generated is reduced by cos(-22.5) = .924

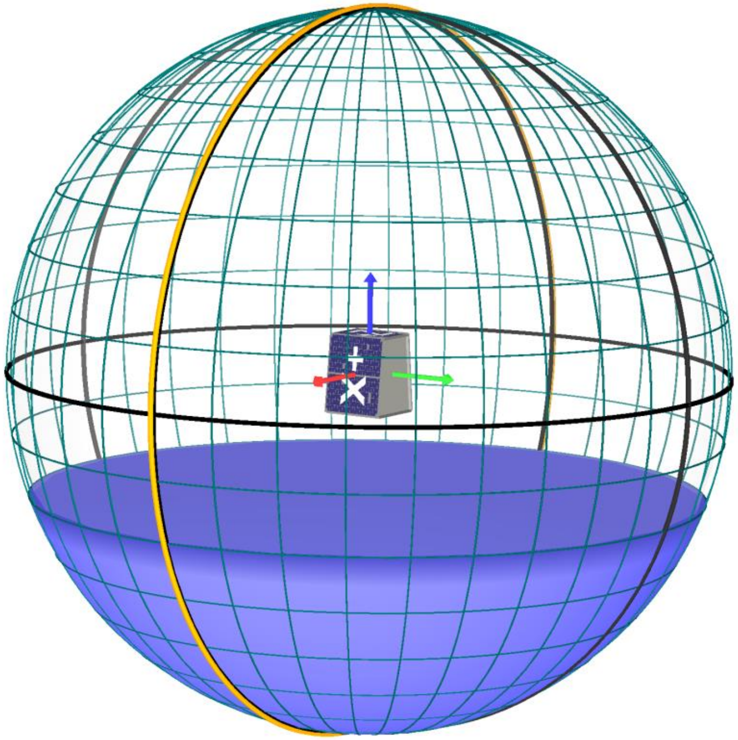
- For the front & back panels, peak power = 224 W * .924 = 210 W
- Orbit Average Power = 70.7W * .924 = 65.3 W

- For the Zenith panel, peak power = 112 W * .924 = 105 W
- Orbit Average Power = 35.4 * .924 = 32.7W

Front Solar Panel Illumination Profile: $\beta = 0°$

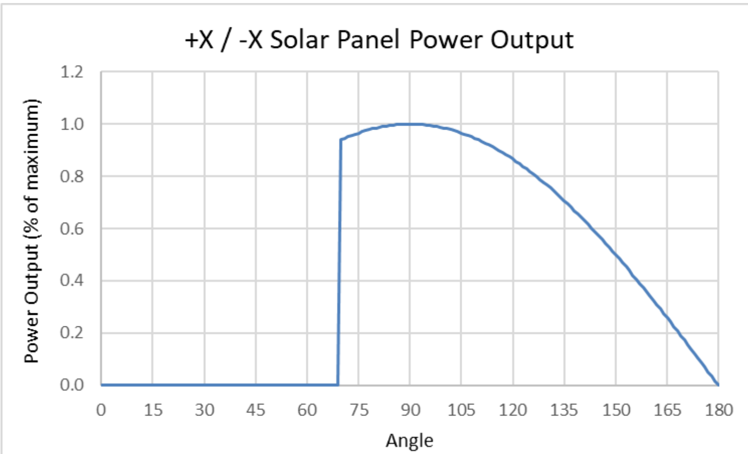
For a +X-facing (front) panel in a noon-midnight orbit:



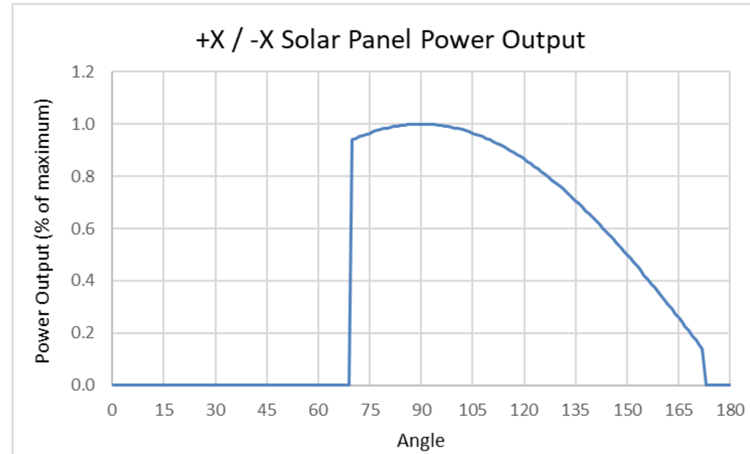


What does the power output profile of the Solar Panel look like (for ρ = 20°)?

+X (Front) Solar Panel Power Output: $\beta = 0°$



or

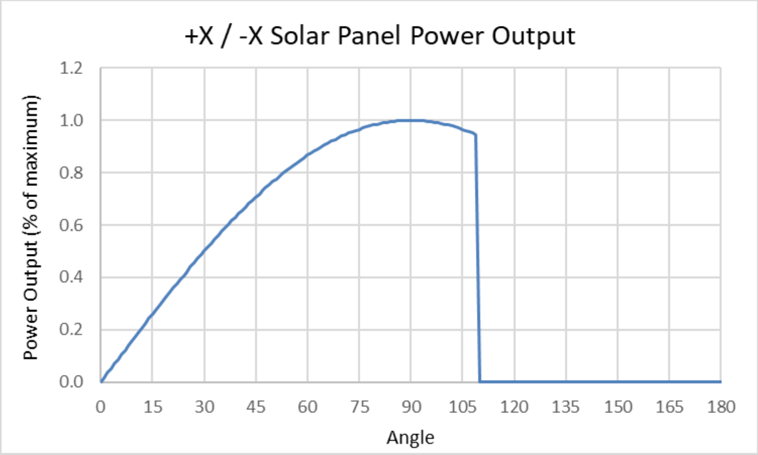


The +X panel produces no power until the sun rises above the Earth's horizon, when the sun angle = 70°. The average power output value is 0.43.

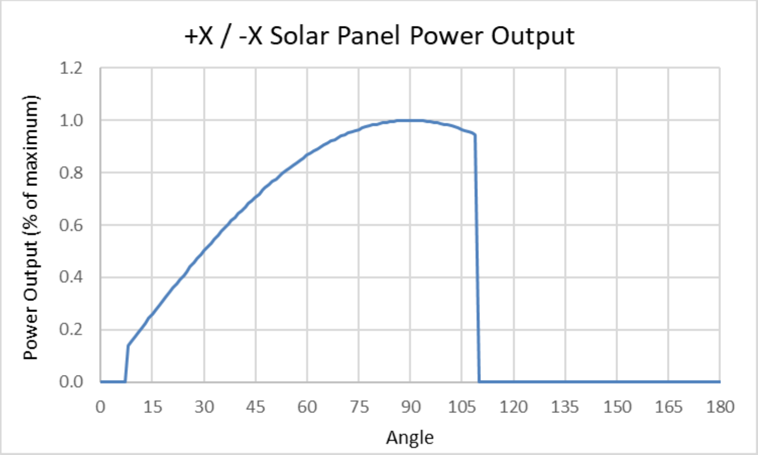
So, for the front (+X) panel:

- Peak Power = 1322 W/m^2 * $1m^2$ * 17% efficiency = 224.7W
- Orbit Average Power = 224.7W * 0.43 * 0.5 = 48.3W (for left graph)
- Orbit Average Power = 224.7W * 0.42 * 0.5 = 48.0W (for right graph)

-X (Back) Solar Panel Power Output: $\beta = 0°$



or



The Back (-X) panel has the opposite power production profile from the +X panel. Thus, its power production is:

- Peak Power = 1322 W/m^2 * 1m^2 * 17% efficiency = 224.7W
- Orbit Average Power = 224.7W * 0.43 * 0.5 = 48.3W (for left graph)
- Orbit Average Power = 224.7W * 0.42 * 0.5 = 48.0W (for right graph)

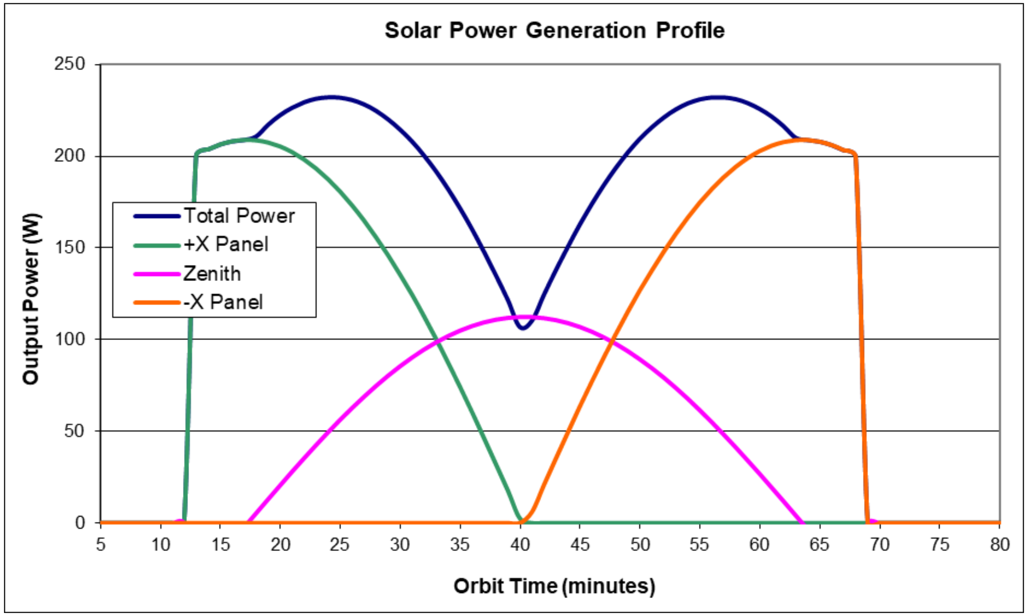
+X/-X Solar Panel Power Output: $\beta = 22.5^\circ$

As with the Zenith-facing panel, for a Beta Angle of -22.5° the power generated is reduced by cos(-22.5) = 0.924.

Thus, the power for the Front (+X) and Back (-X) panels is:

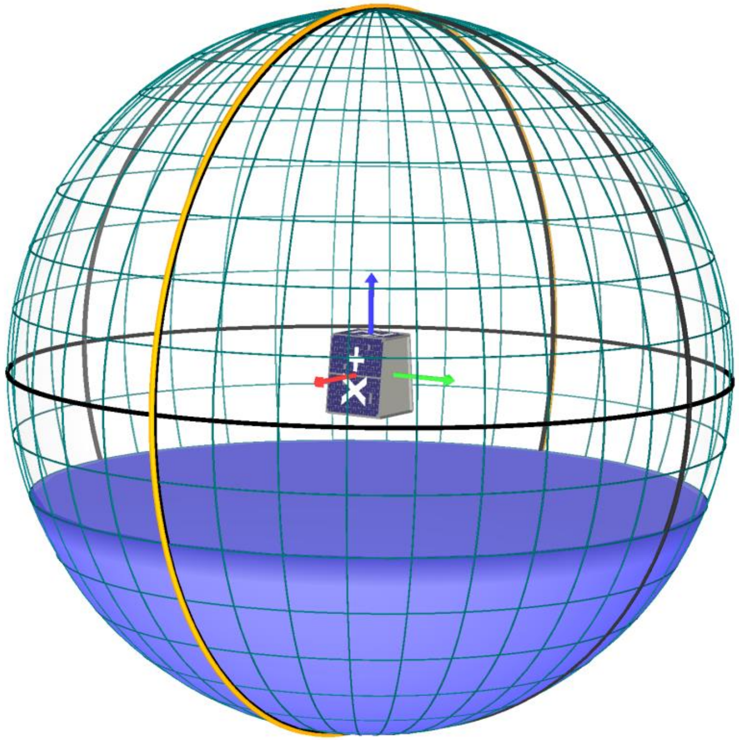
Total Power Generation for Our Mission

- Add up the OAP from all the panels:
  - +X: 48.3 W
  - Zenith: 35.4 W
  - -X: 48.3 W
  - Total: 132.0 W



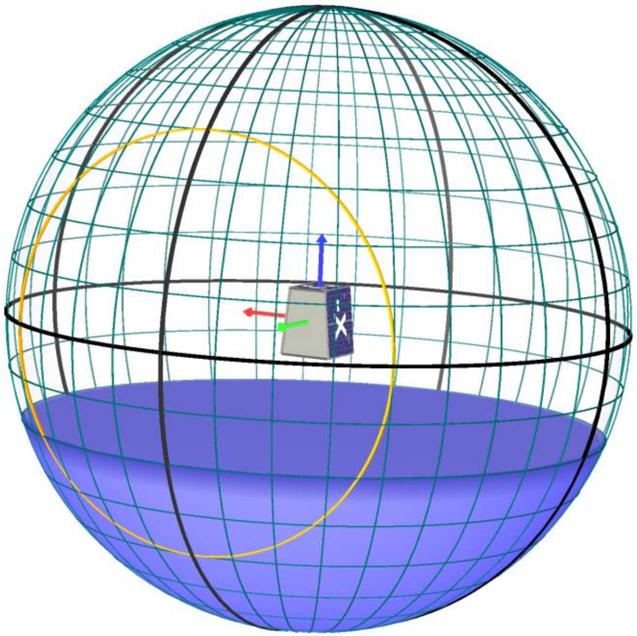
Side Solar Panel Illumination Profile: $\beta = 0°$

For a side-facing (+Y/-Y) panel in a noon-midnight orbit, it would produce no power.



Side Solar Panel Illumination Profile: $\beta = 50°$

For a side-facing (+Y/-Y) panel in a where $\beta = 50°$



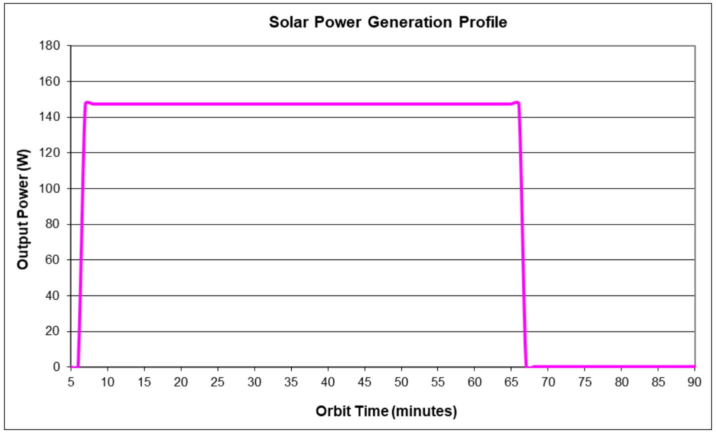
The sun angle on the panel is constant.

The angle is $90° - \beta$ from the panel normal.

Power output = $\cos(90° - \beta)$ * maximum panel power output.

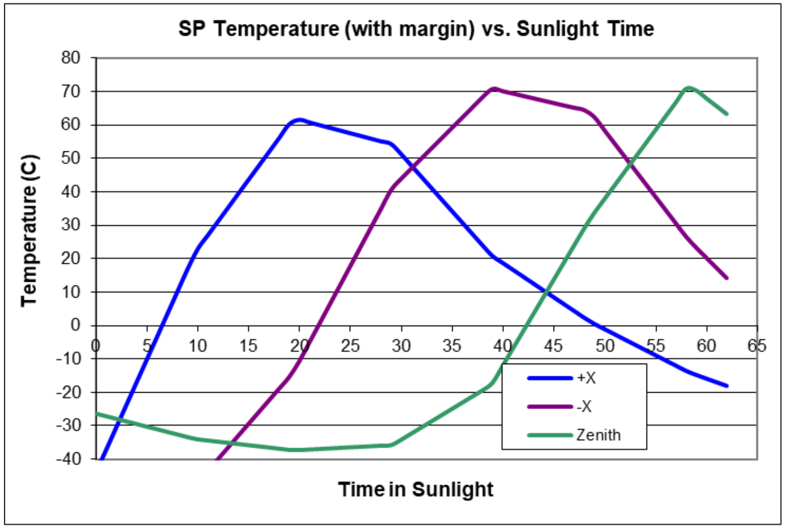
The panel produces power throughout the non-eclipse portion of the orbit.

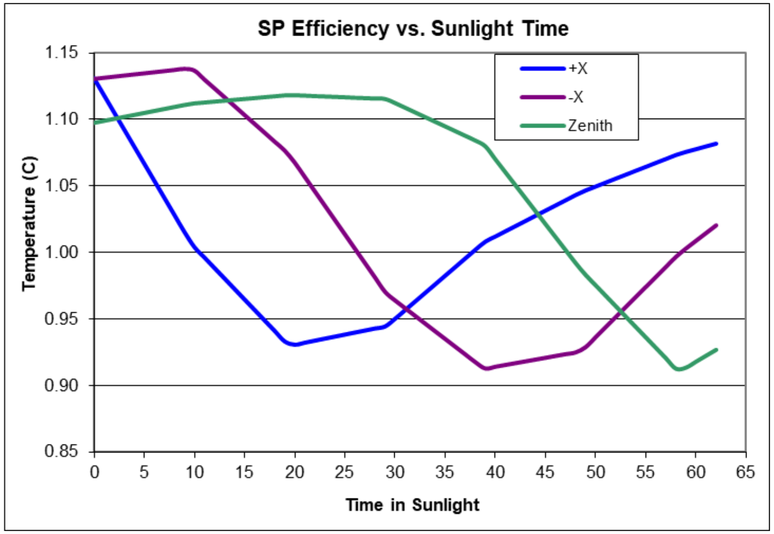
=> OAP = (non-eclipse fraction) * $\cos(90° - \beta)$ * maximum panel power output.



Solar Panel Efficiency vs Temperature

RapidEye solar panel efficiency vs. temperature





Solar cell efficiency is stated for a given temperature (e.g., 20° C).

Efficiency goes down as temperature goes up (~3% for every 20° C). A thermal analysis will be required in order to accurately predict solar panel temperature over the course of an orbit.

You can assume an average temperature & efficiency for the orbit (e.g., 40° C). The more conservative you want to be, the higher average temperature you should use.

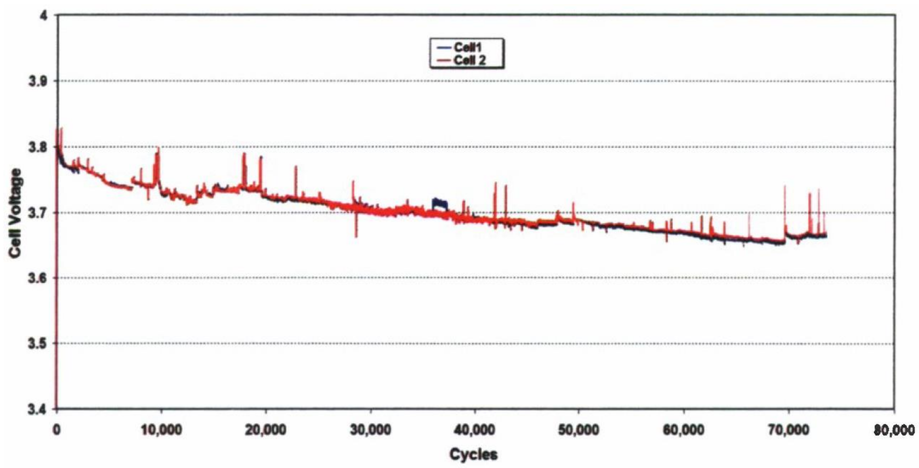
Solar Panel Degradation

- Solar panels will lose their ability to generate power over their mission, due to:
  - Radiation degradation (~1% per year for LEO)
  - Micrometeoroid degradation (~1% per year for LEO)
- This can be exponential (not linear), and will make a big difference when you get into 10+ years on-orbit
- E.g., for a 5-year mission, the degradation will be:
  - $P_{final} = P_{initial} * (1 / 1.02^5) = \sim 90.6\%$
- So, in order to provide 100% power at End-of-Life, you will need:
  - 1 / 0.906 = 110% the amount of solar panel area required at Beginning-of-Life.

POWER STORAGE

Some Notes about Batteries

- You generally only need batteries during eclipse.
- Charge the batteries with the excess power generated.
- What is the charge/discharge efficiency? (~93% for RapidEye). Operation requires more “source” power during eclipse
  - 1 / (0.93*0.93) = 1.156 (i.e., 15.6% more “source” power needed)
- Is there a maximum charge/discharge limit?
- Depth-of-Discharge vs. Cycles – how much does your battery capacity decrease over the mission?



POWER MODELLING

Average & Worst-Cast Power Usage

Component	Power Usage (W)	Duty Cycle	Orbit Average Power (W)	Source?	Margin	Power Usage with Margin	Orbit Average Power (W)	Voltage	Efficiency Factor	Orbit Average Power (W)
Power Control Module	9.0	100.0%	9.0	Spec sheet	5.0%	9.5	9.5	12	98%	9.6
Main CPU (C&DH)	12.0	100.0%	12.0	Measured	2.0%	12.2	12.2	5	66%	18.5
AD&C Cpmpuer	1.5	100.0%	1.5	Spec sheet	2.0%	1.5	1.5	5	66%	2.3
- Reaction Wheels	7.0	100.0%	7.0	Alteration	15.0%	8.1	8.1	12	98%	8.2
- Star Tracker	3.0	100.0%	3.0	Spec sheet	5.0%	3.2	3.2	5	66%	4.8
- GPS	6.0	100.0%	6.0	Measured	2.0%	6.1	6.1	5	66%	9.3
- Magnetometer	1.0	100.0%	1.0	Measured	2.0%	1.0	1.0	5	66%	1.5
- Magnetorquer	4.0	6.7%	0.3	Measured	2.0%	4.1	0.3	12	98%	0.3
						0.0	0.0			
Receiver 1	2.0	100.0%	2.0	Measured	2.0%	2.0	2.0	12	98%	2.1
Receiver 2	2.0	0.0%	0.0	Measured	2.0%	2.0	0.0	12	98%	0.0
Transmitter 1	5.0	3.7%	0.2	Measured	2.0%	5.1	0.2	12	98%	0.2
Transmitter 2	5.0	0.0%	0.0	Measured	2.0%	5.1	0.0	12	98%	0.0
						0.0	0.0			
Payload 1	15.0	30.0%	4.5	Alteration	15.0%	17.3	5.2	12	98.0%	5.3
Payload 2	35.0	10.0%	3.5	New Design	25.0%	43.8	4.4	12	98.0%	4.5
Total			50.0				53.6			66.6

Component	Power Usage (W)	Duty Cycle	Orbit Average Power (W)	Source?	Margin	Power Usage with Margin	Orbit Average Power (W)	Voltage	Efficiency Factor	Orbit Average Power (W)
Power Control Module	9.0	100.0%	9.0	Spec sheet	5.0%	9.5	9.5	12	98%	9.6
Main CPU (C&DH)	12.0	100.0%	12.0	Measured	2.0%	12.2	12.2	5	66%	18.5
AD&C Cpmpuer	1.5	100.0%	1.5	Spec sheet	2.0%	1.5	1.5	5	66%	2.3
- Reaction Wheels	7.0	100.0%	7.0	Alteration	15.0%	8.1	8.1	12	98%	8.2
- Star Tracker	3.0	100.0%	3.0	Spec sheet	5.0%	3.2	3.2	5	66%	4.8
- GPS	6.0	100.0%	6.0	Measured	2.0%	6.1	6.1	5	66%	9.3
- Magnetometer	1.0	100.0%	1.0	Measured	2.0%	1.0	1.0	5	66%	1.5
- Magnetorquer	4.0	50.0%	2.0	Measured	2.0%	4.1	2.0	12	98%	2.1
						0.0	0.0			
Receiver 1	2.0	100.0%	2.0	Measured	2.0%	2.0	2.0	12	98%	2.1
Receiver 2	2.0	0.0%	0.0	Measured	2.0%	2.0	0.0	12	98%	0.0
Transmitter 1	5.0	12.0%	0.6	Measured	2.0%	5.1	0.6	12	98%	0.6
Transmitter 2	5.0	0.0%	0.0	Measured	2.0%	5.1	0.0	12	98%	0.0
						0.0	0.0			
Payload 1	15.0	40.0%	6.0	Alteration	15.0%	17.3	6.9	12	98.0%	7.0
Payload 2	35.0	25.0%	8.8	New Design	25.0%	43.8	10.9	12	98.0%	11.2
Total			58.9				64.1			77.3

OAP Generated = 124.3 W

Power System Timeline

To see the instantaneous state of the power system, you can create a timeline with time-slices calculating the state of power generation & usage.

Time	Mean Anomaly	Sat Lat	Sat Long	Satellite Heading	Azimuth from Sat to SSP	Sun Az from Sat	Sun Elev from Sat	In Sun?	Panel 1 Basic Output	Panel 2 Basic Output	Panel 3 Basic Output	Total Power
12:00 AM	270.0	-0.1	-50.0	352.0	298.5	306.5	-35.5	0	0.0	0.0	0.0	0.0
12:01 AM	273.9	3.7	-50.5	352.0	300.6	308.6	-33.1	0	0.0	0.0	0.0	0.0
12:02 AM	277.8	7.6	-51.1	352.0	302.4	310.4	-30.6	0	0.0	0.0	0.0	0.0
12:03 AM	281.7	11.4	-51.6	351.9	304.0	312.1	-28.0	0	0.0	0.0	0.0	0.0
12:04 AM	285.5	15.3	-52.2	351.8	305.3	313.5	-25.4	0	0.0	0.0	0.0	0.0
12:05 AM	289.4	19.1	-52.8	351.6	306.3	314.8	-22.7	0	0.0	0.0	0.0	0.0
12:06 AM	293.3	23.0	-53.4	351.4	307.2	315.8	-19.9	0	0.0	0.0	0.0	0.0
12:07 AM	297.2	26.8	-54.0	351.1	307.8	316.7	-17.1	1	156.4	0.0	0.0	145.6
12:08 AM	301.1	30.7	-54.8	350.7	308.2	317.5	-14.3	1	160.5	0.0	0.0	149.5
12:09 AM	305.0	34.5	-55.5	350.3	308.4	318.1	-11.4	1	163.9	0.0	0.0	152.6
12:10 AM	308.9	38.3	-56.3	349.8	308.4	318.5	-8.5	1	166.6	0.0	0.0	155.1
12:11 AM	312.8	42.2	-57.3	349.2	308.1	318.8	-5.6	1	168.4	0.0	0.0	156.8
12:12 AM	316.6	46.0	-58.3	348.5	307.5	319.0	-2.6	1	169.5	0.0	0.0	157.8
12:13 AM	320.5	49.8	-59.5	347.6	306.7	319.1	0.3	1	169.8	1.3	0.0	158.2
12:14 AM	324.4	53.6	-60.9	346.5	305.5	319.0	3.3	1	169.4	12.8	0.0	167.0
12:15 AM	328.3	57.4	-62.6	345.1	303.9	318.8	6.2	1	168.1	24.3	0.0	177.0
12:16 AM	332.2	61.1	-64.7	343.4	301.8	318.4	9.1	1	166.1	35.6	0.0	186.0
12:17 AM	336.1	64.8	-67.3	341.0	299.0	317.9	12.0	1	163.3	46.8	0.0	194.1
12:18 AM	340.0	68.5	-70.7	337.9	295.2	317.3	14.9	1	159.7	57.8	0.0	201.4
12:19 AM	343.8	72.0	-75.5	333.4	289.9	316.5	17.7	1	155.4	68.5	0.0	207.7
12:20 AM	347.7	75.4	-82.4	326.7	282.3	315.6	20.5	1	150.4	78.9	0.0	212.9

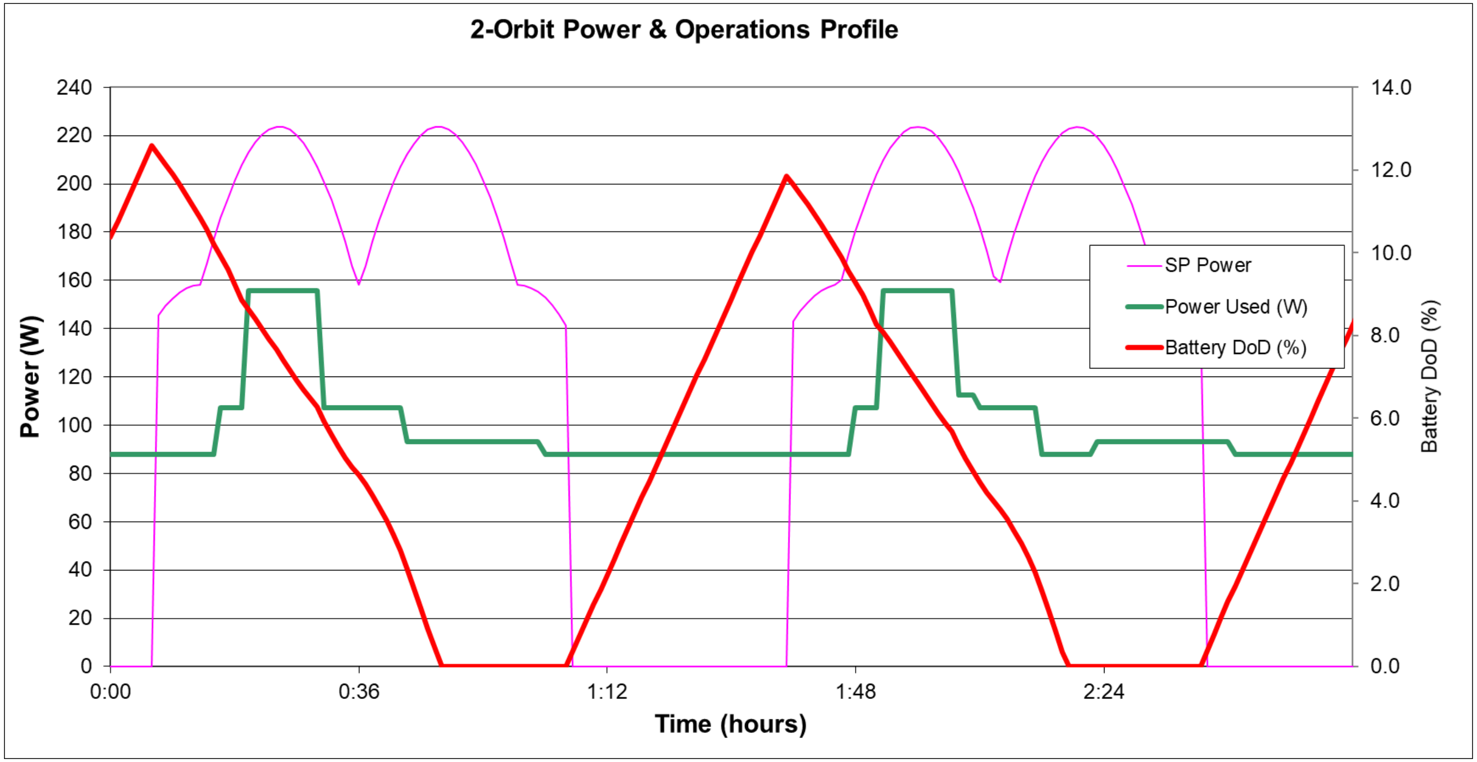
Power System Timeline

Power usage and battery storage…

Time (UTCG)	SP Power	PCM	C&DH	AD&C CPU	RW	STT	GPS	MGM	MTQ	Rx1	Rx2	Tx1	Tx2	PL 1	PL 2
12:00 AM	0.0	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	0.00	0.00
12:01 AM	0.0	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	0.00	0.00
12:02 AM	0.0	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	0.00	0.00
12:03 AM	0.0	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	0.00	0.00
12:04 AM	0.0	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	0.00	0.00
12:05 AM	0.0	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	0.00	0.00
12:06 AM	0.0	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	0.00	0.00
12:07 AM	145.6	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	0.00	0.00
12:08 AM	149.5	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	0.00	0.00
12:09 AM	152.6	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	0.00	0.00
12:10 AM	155.1	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	0.00	0.00
12:11 AM	156.8	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	0.00	0.00
12:12 AM	157.8	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	0.00	0.00
12:13 AM	158.2	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	0.00	0.00
12:14 AM	167.0	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	0.00	0.00
12:15 AM	177.0	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	0.00	0.00
12:16 AM	186.0	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	19.44	0.00
12:17 AM	194.1	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	19.44	0.00
12:18 AM	201.4	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	19.44	0.00
12:19 AM	207.7	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	19.44	0.00
12:20 AM	212.9	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	19.44	48.67
12:21 AM	217.1	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	19.44	48.67
12:22 AM	220.5	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	19.44	48.67
12:23 AM	222.6	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	19.44	48.67
12:24 AM	223.5	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	19.44	48.67
12:25 AM	223.5	16.13	30.83	3.83	8.70	8.00	15.50	2.50	0.00	2.23	0.00	0.00	0.00	19.44	48.67

Power Used (W)	SP Power Available (W)	Power Balance (W)	Charge Power (W)	Charge / Dischrge (W-hr)	Discharge Current (Amps)	Battery level (W-hr)	Battery DoD (%)
87.7	0.0	-87.7	-93.3	-1.56	3.33	376.4	10.4
87.7	0.0	-87.7	-93.3	-1.56	3.33	374.9	10.7
87.7	0.0	-87.7	-93.3	-1.56	3.33	373.3	11.1
87.7	0.0	-87.7	-93.3	-1.56	3.33	371.8	11.5
87.7	0.0	-87.7	-93.3	-1.56	3.33	370.2	11.9
87.7	0.0	-87.7	-93.3	-1.56	3.33	368.7	12.2
87.7	0.0	-87.7	-93.3	-1.56	3.33	367.1	12.6
87.7	145.6	57.9	55.0	0.92		368.0	12.4
87.7	149.5	61.7	58.7	0.98		369.0	12.1
87.7	152.6	64.9	61.7	1.03		370.0	11.9
87.7	155.1	67.4	64.0	1.07		371.1	11.6
87.7	156.8	69.1	65.6	1.09		372.2	11.4
87.7	157.8	70.1	66.6	1.11		373.3	11.1
87.7	158.2	70.5	67.0	1.12		374.4	10.9
87.7	167.0	79.3	75.4	1.26		375.7	10.6
87.7	177.0	89.2	84.8	1.41		377.1	10.2
107.2	186.0	78.8	74.9	1.25		378.3	9.9
107.2	194.1	86.9	82.6	1.38		379.7	9.6
107.2	201.4	94.2	89.5	1.49		381.2	9.2
107.2	207.7	100.6	95.5	1.59		382.8	8.9
155.8	212.9	57.1	54.2	0.90		383.7	8.6
155.8	217.1	61.3	58.2	0.97		384.7	8.4
155.8	220.5	64.7	61.4	1.02		385.7	8.2
155.8	222.6	66.7	63.4	1.06		386.8	7.9
155.8	223.5	67.7	64.3	1.07		387.8	7.7
155.8	223.5	67.7	64.3	1.07		388.9	7.4

Power Usage Profile – Average with Margins



Power Usage Profile – Worst-Case + Average