Mission Definition, Load modes; Initial Power Budget

Orbital Period,T in minutes:

$$T = 84.49 \cdot (\frac{6371 + h}{6371})^{1.5}$$

Given an altitude, h of:

$$h = 500km$$

$$T = 84.49 \times (\frac{6371 + 500}{6371})^{1.5} = 94.629 \approx 95mins$$

The **beta angle (β)** is the angle between the orbit plane and the sun vector. It's arguably **the single most important parameter** for determining a satellite's thermal and power environment.

Low Beta Angle (β ≈ 0° - 30°):

- **Frequent Eclipses:** The orbit plane is nearly edge-on to the sun, so the satellite passes through Earth's shadow on most orbits.
- **Long Eclipse Durations:** Can be up to ~35 minutes for LEO.
- **Power Impact:** This is the **worst-case scenario for power**. We have less time in sunlight to recharge the battery after a long discharge. An example budget with a 30-minute eclipse is representative of a low beta angle.
- **Thermal Impact:** Cyclic heating (sun) and deep cooling (eclipse) are most severe.

High Beta Angle (β ≈ 60° - 90°):

- **Rare or No Eclipses:** The orbit plane is tilted away from the sun, so the satellite may never enter Earth's shadow for weeks or months ("eclipse season" vs. "full sun season").
- **Short or Zero Eclipse Duration**
- **Power Impact:** This is the **best-case scenario for power**. We'll have continuous sunlight, allowing the batteries to stay fully charged and providing abundant power for high-duty-cycle operations.
  Therefore, considering the worst case scenario, when the solar beta angle is **0°** ($\beta = 0°$) (worst case) the eclipse is much longer. To determine the maximum eclipse duration ($T_{eclipse,max}$):

$$T_{eclipse,max} = \frac{T}{\pi} \cdot sin^{-1}(\frac{6371}{6371 + h})$$

$$\therefore T_{eclipse,max} = \frac{94.629}{180°} \times sin^{-1}(\frac{6371}{6371 + 500}) = 35.752\, mins \approx 0.596\, hrs$$

Sunlight duration, T_{sun} :

$$T_{sun} = T - T_{ecliplse} = 94.629 - 35.752 = 58.876\, mins \approx 0.981\, hrs$$

Power Consumption for all Subsystems in various modes

This is the initial power budget sheet POWER_BUDGET.sheet

Mode	Subsystem	Voltage(V)	Peak Current(A)	Peak Power (W)	Average Current (A)	Average Power (W)	Duty Cycle	Orbit Average Power,OAP (W)	Notes
NORMAL	OBC (Raspberry Pi 4)	5	2.5	12.5	0.6	3	1	3	Nominal OBC
	OBC (Low-power)	5	0.2	1	0.2	1	0	0	Sleep/low-power variant (not used in Normal)
	COMM (RFM95) Tx	5	0.8	4	0.8	4	0.05	0.2	Tx bursts
	COMM (RFM95) Rx	3.3	0.1	0.33	0.1	0.33	0.5	0.165	Receiver listening
	ESP32 (Telemetry)	5	0.25	1.25	0.0909	0.4545	0.2	0.0909	ESP32 active fraction
	Camera (Raspberry Cam)	3.3	0.5	1.65	0.5	1.65	0.05	0.0825	Imaging short bursts
	ADCS	5	0.5	2.5	0.15	0.75	0.5	0.375	Reaction wheels / sensors active portion
	EPS & Watchdog	5	0.0005	0.0025	0.05	0.25	1	0.25	Always on
	Other Peripherals	5	0.2	1	0.09	0.45	0.5	0.225	Sensors, LEDs, etc.
	MODE TOTAL			24.2325		11.8845		**4.3884**	OAP (W)
HIGH POWER	OBC (Raspberry Pi 4)	5	2.5	12.5	1.2	6	1	6	OBC under heavy processing

Mode	Subsystem	Voltage(V)	Peak Current(A)	Peak Power (W)	Average Current (A)	Average Power (W)	Duty Cycle	Orbit Average Power,OAP (W)	Notes
	COMM (RFM95) Tx	5	0.8	4	0.8	4	0.5	2	Sustained high-rate Tx bursts
	COMM (RFM95) Rx	3.3	0.1	0.33	0.1	0.33	0.2	0.066	RX listen
	ESP32 (Telemetry)	5	0.25	1.25	0.0909	0.3	1	0.3	ESP32 fully active
	Camera (Raspberry Cam)	3.3	0.5	1.65	0.5	1.65	0.5	0.825	Imaging heavy
	ADCS	5	0.5	2.5	0.15	0.75	0.7	0.525	More ADCS activity
	EPS & Watchdog	5	0.0005	0.0025	0.05	0.165	1	0.165	Always on
	Other Peripherals	5	0.2	1	0.09	0.3	0.5	0.15	Extra sensors
	MODE TOTAL			23.2325		13.495		**10.031**	OAP (W)
LOW POWER (ECLIPSE)	EPS & Watchdog	5	0.0005	0.0025	0.05	0.25	1	0.25	EPS + watchdog only (eclipse safe)
	MODE TOTAL			0.0025		0.25		**0.25**	OAP (W)
SUN SAFE	OBC (Low-power)	5	0.2	1	0.2	1	0.2	0.2	OBC limited activity
	ADCS	5	0.5	2.5	0.15	0.75	1	0.75	ADCS remains active to safe-pointing
	EPS & Watchdog	5	0.0005	0.0025	0.05	0.165	1	0.165	Always on
	Other Peripherals	5	0.2	1	0.09	0.3	0.1	0.03	Minimal peripherals
	MODE TOTAL			4.5025		2.215		**1.145**	OAP (W)
STANDBY	OBC (Low-power)	5	0.2	1	0.2	1	0.2	0.2	Waiting for battery recharge
	COMM (RFM95) Rx	3.3	0.1	0.33	0.1	0.33	0.1	0.033	Occasional listen
	ADCS	5	0.5	2.5	0.15	0.75	0.2	0.15	Minimal pointing
	EPS & Watchdog	5	0.0005	0.0025	0.05	0.25	1	0.25	Always on
	Other Peripherals	5	0.2	1	0.09	0.45	0.1	0.045	Minimal sensors
	MODE TOTAL			4.8325		2.78		**0.678**	OAP (W)
IMAGING (STRIP)	OBC (Raspberry Pi 4)	5	2.5	12.5	0.6	3	1	3	Processing imagery
	COMM (RFM95) Rx	3.3	0.1	0.33	0.1	0.33	0.1	0.033	Housekeeping
	ESP32 (Telemetry)	5	0.25	1.25	0.0909	0.4545	0.5	0.15	Mid activity telemetry
	Camera (Raspberry Cam)	3.3	0.5	1.65	0.5	1.65	0.3	0.495	Strip imaging cadence
	ADCS	5	0.5	2.5	0.15	0.75	0.6	0.45	Pointing during imaging
	EPS & Watchdog	5	0.0005	0.0025	0.05	0.25	1	0.165	Always on
	Other Peripherals	5	0.2	1	0.09	0.45	0.2	0.06	Extra sensors
	MODE TOTAL			19.2325		6.8845		**4.353**	OAP (W)
IMAGING (SPOT)	OBC (Raspberry Pi 4)	5	2.5	12.5	0.6	3	1	3	Processing for spot shots
	COMM (RFM95) Rx	3.3	0.1	0.33	0.1	0.33	0.1	0.033	Housekeeping
	ESP32 (Telemetry)	5	0.25	1.25	0.0909	0.4545	0.8	0.24	ESP32 heavy during spot ops
	Camera (Raspberry Cam)	3.3	0.5	1.65	0.5	1.65	0.1	0.165	Short spot captures

Mode	Subsystem	Voltage(V)	Peak Current(A)	Peak Power (W)	Average Current (A)	Average Power (W)	Duty Cycle	Orbit Average Power,OAP (W)	Notes
	ADCS	5	0.5	2.5	0.15	0.75	0.6	0.45	High accuracy pointing
	EPS & Watchdog	5	0.0005	0.0025	0.05	0.25	1	0.165	Always on
	Other Peripherals	5	0.2	1	0.09	0.45	0.2	0.06	Aux sensors
	MODE TOTAL			19.2325		6.8845		**4.113**	OAP (W)
IMAGING (SCAN)	OBC (Raspberry Pi 4)	5	2.5	12.5	0.6	3	1	3	Continuous processing
	COMM (RFM95) Rx	3.3	0.1	0.33	0.1	0.33	0.1	0.033	Housekeeping
	ESP32 (Telemetry)	5	0.25	1.25	0.0909	0.4545	0.6	0.18	Moderate ESP32 activity
	Camera (Raspberry Cam)	3.3	0.5	1.65	0.5	1.65	0.5	0.825	Scan imaging high duty
	ADCS	5	0.5	2.5	0.15	0.75	0.6	0.45	Continuous pointing
	EPS & Watchdog	5	0.0005	0.0025	0.05	0.25	1	0.165	Always on
	Other Peripherals	5	0.2	1	0.09	0.45	0.2	0.06	Aux sensors
	MODE TOTAL			19.2325		6.8845		**4.713**	OAP (W)
DOWNLINK	OBC (Raspberry Pi 4)	5	2.5	12.5	0.6	3	1	3	Data handling during downlink
	COMM (RFM95) Tx	5	0.8	4	0.8	4	0.8	3.2	High duty Tx
	COMM (RFM95) Rx	3.3	0.1	0.33	0.1	0.33	0.2	0.066	Dual listen
	ESP32 (Telemetry)	5	0.25	1.25	0.0909	0.4545	1	0.3	Full control stacks active
	Camera (Raspberry Cam)	3.3	0.5	1.65	0.5	1.65	0	0	Camera idle during downlink
	ADCS	5	0.5	2.5	0.15	0.75	0.5	0.375	Pointing for comm link
	EPS & Watchdog	5	0.0005	0.0025	0.05	0.25	1	0.165	Always on
	Other Peripherals	5	0.2	1	0.09	0.45	0.2	0.06	Sensors/housekeeping
	MODE TOTAL			23.2325		10.8845		**7.166**	OAP (W)

Battery Capacity

The Average Eclipse Power, $P_{eclipse,avg}$ is the sum of the Orbit Average Power,OAP, for all the subsystems that will be active during eclipse. If we consider the worst case scenario operation during eclipse which is the HIGH POWER MODE and has the highest OAP/ $P_{eclipse,avg}(W)$ of approx. $10\,W$, peak power of $23.2325\,W$ and average power of $13.495\,W$. The Eclipse Energy Requirement , $E_{eclipse}$:

$$E_{eclipse}(Wh) = P_{eclipse,avg}(W) \times T_{eclipse,max}(hrs)$$

$$E_{eclipse}(Wh)_{OAP} = 10.031W \times 0.596\,hrs = 5.9785\,Wh \approx 6\,Wh$$

If we use the raw average power the eclipse energy becomes:

$$E_{eclipse}(Wh)_{avg} = 13.495W \times 0.596\,hrs = 8.043\,Wh \approx 8\,Wh$$

Battery Depth of Discharge(DoD): the DoD should be within a 20%-30%

$$Battery\ Return\ Factor = \frac{1}{DoD} = \frac{1}{0.3} = 3.333$$

$$Battery\ Capacity\ Required(Wh) = E_{eclipse}(Wh) \times Battery\ Return\ Factor$$

$$Battery\ Capacity\ Required\ (Wh)_{OAP} = 6\,Wh \times 3.333 = 19.998\,Wh \approx 20\,Wh$$

$$Battery\ Capacity\ Required\ (Wh)_{avg} = 8\,Wh \times 3.333 = 26.664\,Wh \approx 27\,Wh$$

To get the available energy in sunlight, we sum the energy that will be used during the period the satellite will be in sunlight(runtime) and the energy required to charge the batteries(recharge).

$$E_{charge,\ required} = \frac{E_{eclipse}}{\eta_{charge} \times \eta_{discharge}} = \frac{6Wh}{0.9 \times 0.9} = 7.4074\,Wh$$

$$E_{sun}(Wh)_{OAP} = 10.031W \times 0.981\,hrs = 9.84\,Wh$$

$$Energy\ Required\ in\ Sunlight = 9.8404(runtime) + 7.4074(recharge) = 17.248\ Wh$$

The solar panels don't deliver all their power directly to the bus. There are losses. The "Available Solar Power at Bus" is the power *after* these initial losses.

$$E_{sun\ generated\ (by\ panels)} = \frac{E_{sun,\ required}}{\eta_{system}} = \frac{17.248}{0.9} = 19.164\ (Wh)$$

$$Available\ Power\ at\ Bus\ (W) = \frac{17.248\ Wh}{0.981h} = 17.582\ W$$

Energy Balance Over an Orbit

Energy generated in Sunlight, E_{sun}:

$$E_{sun} = Available\ Solar\ Power\ at\ Bus\ (W) \times T_{sun}\ (hrs) = 17.248\ Wh$$

Energy Consumed in Sunlight, $E_{sun,consumed}$:

$$E_{sun,consumed}(Wh) = OAP\ During\ Sunlight\ (W) \times T_{sun}\ (hrs) = 10.031W \times 0.981h = 9.84\ Wh$$

Energy Available for Charging:

$$E_{charge,\ available} = E_{sun} - E_{sun,\ consumed} = 17.248 - 9.84 = 7.408\ Wh$$

Energy Required for Charging:

$$E_{charge,\ required} = \frac{E_{eclipse}}{\eta_{charge} \times \eta_{discharge}} = \frac{6Wh}{0.9 \times 0.9} = 7.4074\ Wh$$

$$Energy\ Margin = \frac{E_{charge,\ available} - E_{charge,\ required}}{E_{charge,\ required}} = \frac{7.408 - 7.4074}{7.4074} = 0.000081$$

Battery Sizing

Applying a 30% margin to cater for the ageing, and higher than expected. Using the energy required in eclipse, $E_{eclipse} = 6Wh$, and battery capacity required 20 Wh and applying the 30% margin for the OAP and average case:

$$20Wh \times 1.30 = 26Wh$$

For the average case:

$$27Wh \times 1.30 = 35.1Wh$$

Calculating the battery capacity in mAh for both cases:

$$mAh = \frac{Wh}{V_{peak}} \times 1000$$

OAP Case:

$$\frac{26Wh}{7.4V} \times 1000 \approx 3514mAh$$

Average Case:

$$\frac{35.1Wh}{7.4V} \times 1000 \approx 4743mAh$$

Therefore the minimum recommended battery pack capacity to cover the OAP case with 30% margin is 3.6Ah (3600mAh) at a voltage of 7.4V in 2S1P. To cover the average case (35.1Wh) a battery pack capacity of $4.8Ah\ (4800mAh)$ at 7.4V in 2S1P configuration.

Cell/Battery Pack Configuration suggestions

1. Single parallel string 2S1P of a single high capacity cell. This configuration has limited redundancy.

$$2S1P \times 3600mAh = 26.64Wh$$

2. $2S2P \implies$ two cells in parallel per series branch with $3000mAh$. This covers both the OAP case and the average case and offers a more redundancy compared to the 2S1P.

$$6000mAh \times 7.4V = 44.4Wh$$

3. Other configurations include $2S3P$ and $2S4P$.

Solar Array Sizing

From the energy generated by solar panels: $E_{sun\ generated\ (by\ panels)} = 19.164Wh$, $T_{sun} = 0.981h$, The required raw panel power during sunlight before losses, $P_{panels} = 19.164W/0.981h = 19.54W$

Taking the efficiency of Triple Junction GaAs solar cells to be 28% and Mono-crystalline Silicon cells efficiency to be 22%. The Effective Power , $P_{effective}$, from the cells can be calculated as :

$$P_{effective} = TSI \times \eta_{cell} \times f_{incidence} \times f_{degradation}$$

Where:
$TSI = Total\ Solar\ Irradiance$
$\eta_{cell} = Cell\ efficiency$
$f_{incidence} = Incidence\ Factor$
$f_{degradation} = Degradation\ Factor$
To determine the total area of solar cells that is required to harvest the effective power:

$$Area = \frac{P_{panels}}{P_{effective}}$$

Assuming a 1U CubeSat of side $10cm \times 10cm$, we get a face area of $0.01m^2$. Using this we can obtain a the number of equivalent faces and the power per face.

Therefore, using the above information, and $TSI = 1361W/m^2$, $f_{degradation} = 0.8$, $f_{incidence} = 1.0$

GaAS	Mono-Si
$P_{effective} = 1361 \times 0.28 \times 1.0 \times 0.8 = 305.0W/m^2$	$P_{effective} = 1361 \times 0.22 \times 1.0 \times 0.8 = 239.64W/m^2$
$Area = \frac{19.54}{305} = 0.0641m^2$	$Area = \frac{19.54}{239.64} = 0.0816W/m^2$
$Equivalent\ faces = \frac{0.0641}{0.01} = 6.41faces$	$Equivalent\ faces = \frac{0.0816}{0.01} = 8.16faces$
$Power\ per\ face = 0.01 \times 305 = 3.05W/face$	$Power\ per\ face = 0.01 \times 239.64 = 2.396W/face$

> In conclusion, when procuring the 18650 cells and Solar cells, we should look for ones with the above specifications.