Astro 331 Prelab 1: Electrical Power

Lt Col Jordan Firth

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Documentation:

- DFAS writing guide (I used to write these instructions—you should read it but don't need to list it in your documentation statement)
- Cite references as necessary, but don't include course notes, course text (SMAD), or these instructions as documentation
- Don't forget to update your own documentation statement when you write your prelab report!

Objective

FlatSAT will operate for 3 years in a 500 km orbit. Its solar panel must provide enough power to operate the spacecraft during that time. The purpose of this lab is to quantify the performance of FlatSAT's solar array and validate that it will meet mission requirements.

Nomenclature

A = area (m^2)

a = semi-major axis (km)

E_e = irradiance (W/m^2)

E_v = illuminance (lm/m^2)

h = orbital altitude (km)

I_d = inherent degradation

K = luminous efficacy (lm/W)

P = power (W)

Per = orbital period (s)

R_e = Earth's radius (km)

S = solar irradiance (W/m^2)

T = time (s)

β = beta angle (°)

η = efficiency

μ = Earth's gravitational parameter ($km^3/s^{2)}$

Φ = eclipse fraction (°)

ρ = Earth's orbital radius (°)

Subscripts

BOL = beginning of life

d = daylight

e = eclipse

EOL = end of life

req = required

Approach

FlatSAT's solar array, shown in Figure 1, consists of four silicon photovoltaic cells. The cells can be connected in series (4S) or parallel (4P).

During this lab, the team will use take current and voltage measurements from FlatSAT's solar array, connected both in series and in parallel. Initial measurements were taken with a digital multimeter to establish the expected limits. Further measurements will be taken with a current sensor connected to an Arduino microcontroller.

The solar array will be wired in series with the current sensor and a 10 kΩ potentiometer. The potentiometer's resistance will be varied to measure multiple current and voltage at multiple points on the I-V curve.

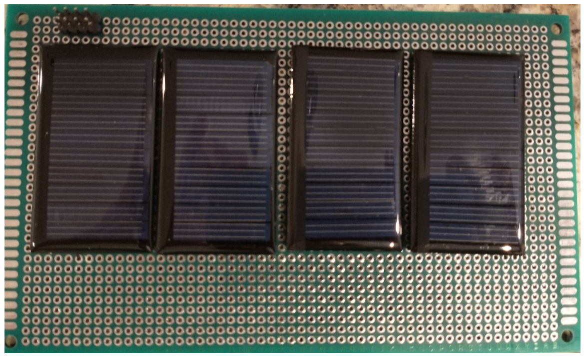

Fig. 1 FlatSAT's solar array

Efficiency will be measured by comparing the array's measured output power to incident radiation. The irradiance of the light source—sunlight or a halogen lamp, depending on weather—will be determined with a luxmeter.

Assumptions

The spacecraft is assumed to be in a circular orbit. Array power will be calculated using SMAD's value for solar input: $1367\,\mathrm{W/m^2}$. The energy output measured during this lab will be slightly lower because the incoming light will be attenuated by the atmosphere.

Math Technique

To ensure that the solar array will provide enough power, the array's end-of-life output must be compared to the spacecraft's power needs.

Spacecraft power requirement

As mentioned earlier, the solar array must provide enough power to operate the spacecraft during each orbit. However, the solar array only produces power during daylight. It must produce one orbit's worth of energy during only the daylight portion of the orbit.

FlatSAT spends a portion of each orbit in the Earth's shadow. This fraction, Φ, depends on the angular size of Earth, ρ from the spacecraft's orbital altitude. Eclipse time also varies with the beta angle, β, which is the angle between the sun vector and its projection onto the orbital plane. Beta angle changes over time for all orbits except equatorial and sun-synchronous orbits. A spacecraft experiences the longest eclipses when $\beta = 0$, which will be used to determine the worst case eclipse length. FlatSAT will operate in a circular orbit at an altitude of 500 km, which is a semi-major axis of 6878.137 km.

$$\rho = \arcsin \frac{R_e}{R_e + h} \tag{1}$$

$$\Phi = 2 \arccos \frac{\cos \rho}{\cos \beta} \tag{2}$$

Period, Eclipse time, and Daylight time are found using Equations 3–5.

$$Per = 2\pi \sqrt{\frac{a^3}{\mu}} \tag{3}$$

$$T_e = Per \frac{\Phi}{360^\circ} \tag{4}$$

$$T_d = Per - T_e \tag{5}$$

Power required from the solar arrays is found using Equation 6.

$$P_{req} = \frac{P_e T_e}{\eta_e T_d} + \frac{P_d}{\eta_d} \tag{6}$$

Power system efficiency, η, varies between eclipse and daylight. Efficiency during daylight measures the system's efficiency converting input voltage to output voltage. Efficiency during eclipse is always worse because it must also include the round-trip energy loss caused by storing and retrieving energy from the energy storage system, in this case a secondary cell battery. FlatSAT uses direct energy transfer, so $\eta_e = 0.65$ and $\eta_d = 0.85$ [1].

Solar array output

The solar array's beginning of life power output is given by Equation 7.

$$P_{BOL} = S\eta I_d \cos\theta A \tag{7}$$

where θ is the panel's incidence angle, or angle between the sun vector and the panel's normal vector.

Solar cells degrade as they are exposed to solar radiation. Array output at any point in the spacecraft's orbital lifetime is calculated using Equation 8. End of life Power, P_{EOL} is found by calculating P with *elapsed years* equal to mission life, in this case 3 years.

$$P = P_{BOL}\,(1 - \textit{annual degradation})^{\textit{elapsed years}} \tag{8}$$

Efficiency

Solar array efficiency is a ratio of the array's areic power to the irradiance of the incident radiation.

$$\eta = \frac{P_{\text{panel}}}{A_{\text{panel}} E_e} \tag{9}$$

A luxmeter measures illuminance in lux. $1\,\text{lx} = 1\,\text{lm/m}^2$. The lumen is the SI unit of brightness, which weights light by wavelength according to the standard luminosity function of human visual perception. Illuminance can be converted to irradiance with Equation 10.

$$E_e = \frac{E_v}{K} \tag{10}$$

For unfiltered sunlight, luminous efficacy, K, is 122 lm/W [2]. For incandescent halogen worklight bulbs, it is 19.3 lm/W [3].

Theoretical Predictions

Based on the orbital energy model described in the previous section and the parameters given in Appendix A, FlatSAT's solar arrays must produce 6.575 W.

Based on the solar array model and the parameters in Table 6, FlatSAT's four-cell solar array will provide 600 mW at beginning of life, and only 535 mW at the end of its three year mission.

Calculations supporting these numbers are shown in Appendix B.

The predicted current-voltage (I-V) curves for this solar array in series and parallel are shown in Figure 2, along with the curve for a single cell. Peak power points, PP, are labelled for each configuration, as well as the short circuit current, I_{sc}, and open circuit voltage, V_{oc}. Key array parameters are summarized in Table 1.

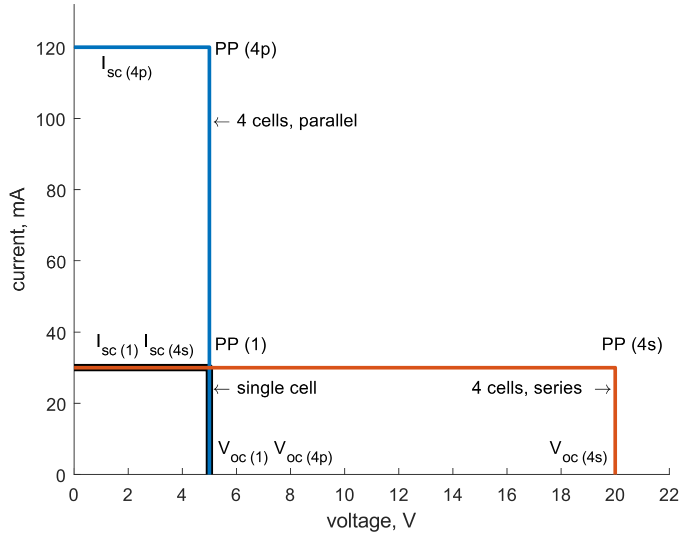

Fig. 2 I-V curve for single cell, 4s, and 4p solar arrays

Table 1 Predicted array output

	V_{oc} (V)	I_{sc} (mA)	P (mW)
series	20	30	600
parallel	5	120	600

Experimental Setup

Solar array output will be measured under full solar illumination with the solar array wired in parallel and again with the solar array wired in series. A luxmeter will provide an accurate value for solar input. Current and voltage measurements will be sent to an Arduino MKR Zero and recorded on an SD card for later analysis. An LCD display will provide real-time data, which will be recorded for backup purposes.

Output will be measured with an INA219 shunt-type current sensor mounted on an Adafruit breakout board. This high side DC current sensor calculates current and voltage using Ohm's law from the measured voltage drop across a $0.1\ \Omega$ precision resistor. The INA219 has an internal 12-bit analog to digital converter (ADC) and provides $\pm 1\%$ precision over its range of 0–3.2 A and 0–26 V. It communicates with the microcontroller via the I2C protocol.

Preliminary Results

!Remove this section for your final lab report, after you have data!

Preliminary open-circuit voltage and short-circuit current measurements were taken with a digital multimeter to determine the expected measurement range and select appropriate sensors. These measurements are shown in Table 3.

Experimental Results

!This section should not appear in your prelab report, but should be in your final lab report!

Table 2 Caption

Table 3 Preliminary electrical measurements

	V_{oc} (V)	I_{sc} (mA)
series		
parallel		

!Your results section should be more comprehensive than this example!

Figure 3 shows the solar array's output when wired in series. Summary results are shown in Table 4. The voltage is slightly higher than expected, but the current is much less than expected.

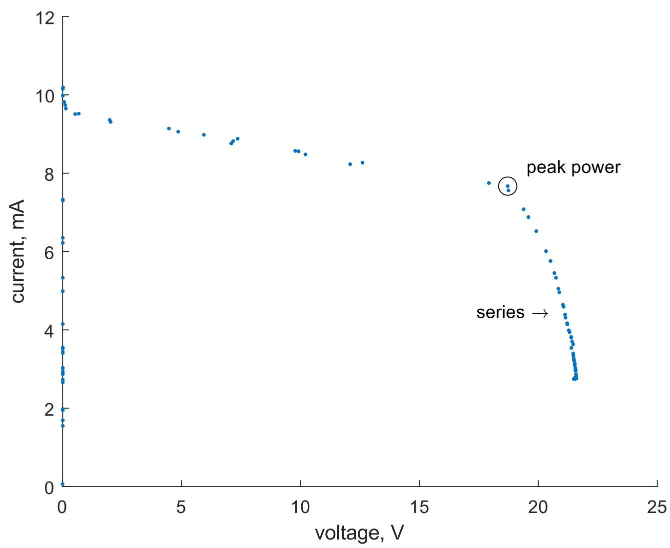

Fig. 3 Series I-V curve

Table 4 Electrical measurements

	V_{oc} (V)	I_{sc} (mA)	peak power (mW)	efficiency (%)
series	21.5	10.19	143.5	
parallel				

Discussion

!This section should appear in your prelab *and* final lab report, but it will be more thorough in the final report!

FlatSAT's solar array will not provide nearly enough power to operate FlatSAT, even at the beginning of its lifetime. The problem will get worse over the spacecraft's lifetime. Based on predicted end of life values, FlatSAT's solar array will provide only 8.14% of FlatSAT's required power.

Based on preliminary measurements, the solar cells provided slightly more voltage than should be expected from their specifications. However, they provided significantly less current than expected.

Conclusion and Recommendations

FlatSAT's 4-cell solar array is completely inadequate. A solar array with the same cells would need to be 12.3 times the size of the current array to power the spacecraft throughout its mission life. This would take a total of 50 cells. Adding an array of this size to FlatSAT would require deployable solar panels, drastically increasing mission complexity.

Increasing efficiency and decreasing inherent degradation would allow the use of a small panel, but these gains would likely be insufficient and/or cost-prohibitive. Instead, the FlatSAT program should pursue power reduction strategies to reduce required power both in and out of eclipse.

References

[1] Larson, W. J. and Wertz, J. R., editors, *Space Mission Analysis and Design*, Springer, 3rd ed., 1999.

[2] Michael, P. R., Johnston, D. E., and Moreno, W., "A conversion guide: Solar irradiance and lux illuminance," *Journal of Measurements in Engineering*, Vol. 8, No. 4, 2020, pp. 153–166.

[3] Philips Lighting, *Plusline Small*, 9 2022, https://www.lighting.philips.com/api/assets/v1/file/PhilipsLighting/content/fp924735544280-pss-global/924735544280_EU.en_AA.PROF.FP.pdf retrieved 2022-02-11.

Appendix A: Key parameters

Table 5 Mission, orbit, and spacecraft parameters

Mission life	3 years
Power in eclipse	2 W
Power in sunlight	4 W
Power regulation	direct energy transfer
Worst sun incidence angle	25°
Worst beta angle	0°

Table 6 Cell & panel parameters (*single cell)

Dimensions*	53 mm × 33 mm
Short-circuit current*	30 mA
Open-circuit voltage*	5 V
Efficiency	14.8%
Inherent degradation	46.78%
Cells	4
connection	series & parallel

Appendix B: theoretical calculations

```
clearvars; clc;
format compact
```

calculate power required from solar array

```
% constants
Re = 6378.137; % (km)       Earth's radius
mu = 398600.5; % (km^3/s^2) Earth's gravitational constant

% given
h = 5e2; %  (km)    orbital altitude
beta = 0; % (deg)   orbital plane angle
Pe = 2; % (W) power required in eclipse
Pd = 4; % (W) power required in daylight

% from SMAD--just after Eqn 11-5
etaE = 0.65; % (unitless) elec efficiency during eclipse
etaD = 0.85; % (unitless) elec efficiency during daylight

% calculations
a = Re + h; % (km) semi-major axis

rho = asind(Re/(Re+h)) % (deg) Earth's angular radius


Phi = 2* acosd(cosd(rho)/cosd(beta)) % (unitless) eclipse fraction

Per = 2*pi* sqrt(a^3/mu) %  (sec)   orbital period
Te = Per * Phi/360 %        (sec)   time in eclipse
Td = Per - Te %        (sec)   time in daylight

P_req = (Pe*Te/etaE + Pd*Td/etaD) / Td % (W) power required from array
```

```
rho =
   68.0187
Phi =
  136.0373
Per =
   5.6770e+03
Te =
   2.1452e+03
Td =
   3.5318e+03
P_req =
    6.5748
```

calculate power provided by arrays

```
% constants
S = 1367; % (W/m^2) solar irradiance
```

```
% given
eta = 0.148; % (unitless) solar cell efficiency
A = 4 * 0.053 * 0.033; % (m^2) solar array area
Id = 0.4677 ; % (unitless) cell inherent degradation
theta = 25 ; % (deg) worst-case incidence angle
life = 3; % (yr) mission life

% from SMAD
degrade = 0.0375; % (/yr) annual degradation

Pbol = S* eta * Id * cosd(theta) * A
Peol = Pbol *(1-degrade)^life
```

```
Pbol =
    0.6000
Peol =
    0.5350
```

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Appendix C: Matlab code for IV predictions

```
clearvars; clc;

cells = 4;
single.i = [30, 30, 0];
single.v = [0, 5, 5];

series.i = single.i;
series.v = cells * single.v;

parallel.i = cells * single.i;
parallel.v = single.v;


figure(1); clf ; hold on;

plot(single.v, single.i,'k', 'LineWidth',4)
 ax = gca; ax.ColorOrderIndex = 1;
plot(parallel.v, parallel.i, 'LineWidth',2)
plot(series.v, series.i, 'LineWidth',2);

xlim([0, 22])
ylim([0, 132])

xlabel('voltage, V')
ylabel('current, mA')

% label each curve
text(5.1, 25, '\leftarrow single cell')
text(5.1, 100, '\leftarrow 4 cells, parallel')
text(19.9, 25, '4 cells, series  \rightarrow', ...
    'HorizontalAlignment','right')

% label open circuit voltage
text(5.3, 7, 'V_{oc (1)} V_{oc (4p)}')
text(19.7, 7, ' V_{oc (4s)}', ...
    'HorizontalAlignment','right')

% label short circuit current
text(0.8, 37, 'I_{sc (1)} I_{sc (4s)}')
text(0.8, 115, ' I_{sc (4p)}')

% label peak power points
text(5.2, 37, 'PP (1)')
text(5.2, 120, 'PP (4p)')
text(19.5, 37, 'PP (4s)')

saveas(gcf, 'iv_prediction.svg')
```

Appendix D: Matlab code for experimental data

```
clearvars; clc;
load('iv_data');

figure(1); clf; hold on

iv2.power = iv2.currentmA .* iv2.voltageV;
[~,pp] = max(iv2.power);

series_peak = iv2.power(pp)

plot(iv2.voltageV, iv2.currentmA, '.')
plot(iv2.voltageV(pp), iv2.currentmA(pp), 'ko', ...
    'MarkerSize', 10)

xlabel('voltage, V')
ylabel('current, mA')

text(20.5 ,4.5, 'series \rightarrow', ...
    'HorizontalAlignment','right')
text(19.5, 8.2, 'peak power')

saveas(gcf, 'iv_curve.svg')
```