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UASat Solar Array Design and Performance Characteristics

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***Abstract-** The traditional power source of earth orbiting spacecraft is the solar photovoltaic. Mission life, orbital parameters, spacecraft configuration, and average and peak electrical power requirement all affect design. This paper investigates the temperature and irradiance effects on the Silicon and Gallium Arsenide solar array. This study is important to achieve the operation of the satellite under extreme space environment and light in weight. Also the design of the solar array and the storage battery are presented. Therefore, UASat (A STUDENT SATELLITE PROJECT) is selected for this goal which helps constrain global climate and global warming models; locate areas of deep atmospheric convection. In addition, they help constrain atmospheric chemistry and space physics models. The study demonstrates that the optimum conditions for the space application to operate near to the room temperature which increases the conversion efficiency.*

***Index Terms-** Silicon, GaAs, Temperature effect, irradiance effect, Low Earth Orbit.*

I. INTRODUCTION

Solar cells have many characteristics that would affect the reliability of producing power for satellites. Power in a solar panel is made up of photovoltaic (PV) cells connected in series to build up a desired voltage. PV cells are devices that are capable of converting sunlight into electrical energy.

Our case study introduces UASat, The Student Satellite Project (SSP) at the University of Arizona was initiated on November 7, 1996, by Department of Physics Professor K.C. Hsieh and Aerospace and Mechanical Engineering Professors Wayne Chen and Ernie Fasse. UASat was formally adopted in February of 1998 [1].

The purpose of UASat is [1]:

1- To detect and locate large areas of lightning activity over the Earth's surface. This includes cloud-to-ground, cloud-to-cloud, and intra-cloud lightning. An orbital platform for these observations represents a significant advantage since ground-based methods can only detect cloud-to-ground lightning strikes.

The data obtained will help constrain global climate and global warming models. They will also help to develop theoretical algorithms that describe the electrical, microphysical and kinematic properties of tropical thunderstorms. Lastly, the data will help locate areas of deep atmospheric convection.

2- UASat hopes to make a significant contribution to the knowledge base on sprites by observing and imaging sprites and investigating correlations between:

- Sprite Production over Land vs. Ocean.
- Frequency of Sprites (Relative to Cloud Flashes) vs. Latitude, Season, Storm Intensity.
- Frequency of Sprites vs. Cloud-to-Ground Strikes.

UASat also hopes to use the sprite data to help constrain atmospheric chemistry and space physics models, and to determine if sprites can occur over single thunderstorm cells as opposed to mesoscale convective systems.

3- Aims to make observations that will improve the accuracy of ground-based measurements of UBVRI colors for a selected set of standard stars. The primary goal is to obtain and publish an internally consistent data set spanning a range of magnitudes in the northern and southern hemispheres.

The amount of electrical energy produced by the PV cells depends on a wide number of factors. These factors include the type of PV material, the material covering the cells, and the effects of radiation, temperature and shading on the cells.

This paper concentrates on a solar array design which will provide power for the operation components on a satellite. The goal of this design is to provide the satellite with a reliable source of power, operational under extreme space environment and light in weight. Also, this paper studies the two important factors radiation and temperature which affect the PV cells.

II. SOLAR ARRAY DESIGN

For Earth orbiting spacecrafts, photovoltaics are the dominant power source because the sun emits large amounts of useful solar energy. A solar array must be designed so that the spacecraft's power needs during daylight and eclipse phases are met [2].

UASat specifications are used in the power generation system as follows:

Altitude = 400 Km, 51.6 degree.
Time per orbit = 90 min.
Time per orbit in the sun = 45 min.
Time per orbit in eclipse = 90 min ─ 45min = 45 min.
Life span of the UASat = 6 months to 15 months.

UASat data are used in our design process,

- Assuming the average power requirement of 150W during daylight and eclipse, $P_e = Pd = 150$ W.
- The efficiencies during daylight and eclipse are approximately at peak power tracking, Xd = 0.8, Xe = 0.6 [3].
- The degradation per year for GaAs = 0.0275 [2].
- The worst case for inherent degradation = $I_d = 0.77$ [2].

The first step for solar array deign is to select its type. Gallium arsenide (GaAs) is that proposed material for LEO, which is 40% more efficient than silicon. GaAs is also more resistant to radiation than Si. The only drawback to GaAs cells is their cost, which is nine to ten times that of silicon cells. The big savings come from the launch costs, where a smaller and lighter GaAs array can satisfy the same power needs as a larger and heavier Si array [2, 4].

The second step is to determine the total amount of power the array must provide during its operational periods by summing the power requirements of the spacecraft during daylight and the charge necessary in secondary batteries so that the eclipse power needs can be met. P_{Sa} can be obtained using equation (1):

$$P_{Sa} = \frac{\frac{P_e T_e}{X_e} + \frac{P_d T_d}{X_d}}{T_d} = 437.5\ Watt \qquad (1)$$

Where:

P_e and P_d: are the spacecraft power requirements during eclipse and daylight respectively.

T_e and $T_{d:}$ are the periods in eclipse and daylight per orbit respectively.

X_e is the efficiency with which the spacecraft can relay power from the array to the battery to the loads in eclipse.

X_d: is the efficiency with which the spacecraft can relay power from the array to the loads in daylight.

The third step is to calculate the output power per unit area, Po by multiply the efficiency of the PV material by the solar constant where Gallium arsenide cell efficiencies are 18.5% as follows:

$$P_O = solar\ \text{int}\, ensity \times \eta_{GaAs} = 252.895\ \ Watt / m^2 \qquad (2)$$

The fourth step is to estimate the power needed at beginning of life using equation (3) as follows:

$$P_{Bol} = P_O I_d \cos\theta = 119.86\ \ Watt \qquad (3)$$

Where: I_d: is the inherent degradation of the solar cell which depends on the design efficiencies, shadowing, and temperature variations, and Θ is the sun incidence angle from the solar panel normal vector [1].

The fifth step is to calculate the power production capacity at EOL. Before calculating the power at EOL, the lifetime degradation must first be calculated using equation (4):

$$L_d = \left(1 - \frac{\deg radation}{year}\right)^{Satellitel\, ife} = 0.9657 \qquad (4)$$

Now the power at end of life can be calculated using equation (5) as below:

$$P_{EOL} = 115.74884 \quad Watt \qquad (5)$$

The sixth step is to calculate the solar array area using equation (6):

$$A_{Sa} = \frac{P_{Sa}}{P_{EOL}} = 3.7797 \quad m^2 \qquad (6)$$

The final step is to estimate the mass of the solar array using equation (7), if the specific performance of the planar array is 25 W/Kg:

$$Ma = \left(\tfrac{1}{25}\right) P_{Sa} = 17.5 \quad Kg \qquad (7)$$

III. SOLAR ARRAY SIZING

Solar array sizing plays an important role the spacecraft design. The sizing of solar array is to determine the number of cells in series and the number of parallel strings. The solar array sizing can be given by the following equations. The solar array consists of GaAs solar cells has the following data from spectrolab [5]:

The power of the solar array, P_{Sa} = 437.5 Watt. The bus voltage, V_{bus} = 28 Vdc. I_{Sa} = 15.625 A, P_{Cell} = 1.2593 W, I_{Cell} = 1.4014 A., V_{Cell} = 0.9 V. The total number of GaAs cells in the solar array can be obtained as follows [6]:

$$N = \frac{P_{Sa}}{P_{Cell}} = 347.4 \cong 348 \qquad (8)$$

Also the number of GaAs PV cells in series, N_S can be determined as follows:

$$N_S = \frac{V_{Sa}}{V_{Cell}} = 32 \qquad (9)$$

The number of parallel strings, N_P can be obtained as bellow:

$$N_P = \frac{I_{Sa}}{I_{Cell}} = 12 \qquad (10)$$

IV. BATTERY SIZING

Energy storage is an integral part of the power subsystem. Spacecrafts using photovoltaic cells or solar thermal dynamics for power require energy storage for peak-power demands and eclipse periods. Storage devices provide power for entire missions of duration less than one week or back-up power for longer mission.

The data needed the sizing process of the batteries as follows: P_{Sa} = 440 Watt, T_e = 45 min, V_{Cell} = 1.25, assuming DOD = 65 %, NiCd specific energy density = E_d = 25 Wh/Kg, V_{bus} = 28 Vdc.

The first step is to select the type of the secondary batteries such as Nickel Cadmium, Nickel Hydrogen, Lithium Ion, and sodium Sulfur. NiCd batteries are still common secondary storage devices for many applications [1]. They have been space qualified and there are extensive database for most missions.

The second step is to determine the number of cells needed in the battery, N, can be obtained using equation (11), assuming one battery used:

$$N = \frac{V_{bus}}{V / _{Cell}} = 22.4 \qquad (11)$$

The number of cells is rounded down to 22 to avoid overloading the bus voltage; V_B can be obtained using equation (12) as follows:

$$V_B = N \times V /_{Cell} = 27.5 \quad Vdc \qquad (12)$$

The third step is to calculate the total capacity, C of the battery from equation (13):

$$C = \frac{(load\ power)\,(Disch\text{arg}\,e\ time)}{(Depth\ of\ Disch\text{arg}\,e)\,(Battery\ Average\ Disch\text{arg}\,e\ Voltage)} = 18.46 \quad Ah \qquad (13)$$

Yielding a battery capacity, C_B from equation (14):

$$C_B = C \times V_B = 507.65\ \ Wh \qquad (14)$$

The last step is to estimate the NiCd battery mass from equation (15):

$$m = \frac{C_B}{E_B} = 20.3 \quad Kg \qquad (15)$$

V. THE EFFECT OF SOLAR INTENSITY ON THE SOLAR ARRAY OF UASAT

The solar intensity varies between 250 W/m^2 and 1350 W/m^2 while the operating temperature remains constants nearly 28 ^{0}C. the PV modified model is applied at the following condition:

T = 28 ^{0}C, Rad = 250 W/m^2 to 1350 W/m^2, N_P = 12, N_S = 32, Solar array Area = 3.7 m^2.

V. 1. CHARACTEISTIC CURVE &POWER CURVE

The photovoltaic modified model is applied to simulate the results of temperature and radiation effects using Matlab® [7]. Fig. 1 shows the effect of the solar intensity variation on GaAs solar array. It is clearly that the solar intensity drops, the IV characteristic curve of the array will shift inward which decreases the output power of the solar array as depicted in Fig. 2.

V. 2. PV PARAMETERIC ANALYSIS

The solar intensity versus the short circuit current of PV array is represented in Fig. 3. The short circuit increase linearly with the solar intensity due to the strongly increase in the light generated current. I_{SC} increases nearly 3 A at 250 W/m^2 up to 18.5 A at 1350 W/m^2.

The relation between the open circuit voltage of PV array is indicated in Fig. 4 the open circuit voltage increases slightly about 30.8 v at 250W/m^2 up to 32.2 V at 1350 W/m^2. The slight increase in the open circuit voltage can be neglected.

Fig. 5 shows the solar intensity versus the maximum output power which increases linearly with the solar intensity nearly about 75 W at 250W/m^2 up to 475 W at 1350 W/m^2. The effect of the solar intensity with the PV array is represented in Fig. 6. The fill factor increases slightly from 0.8005 at 250 W/m^2 up to 0.8015 500 W/m^2 which a noticeable decrease from 0.8015 at 500 W/m^2 down to 0.7955 at 1350 W/m^2. The maximum conversion efficiency versus the solar intensity is illustrated in Fig. 7. It is clearly to be noted that the efficiency increase with the solar intensity which about 8.6 % up to 9.1 %.

VI. THE EFFECT OF TEMPERATURE ON THE SOLAR ARRAY OF UASAT

VI. 1 IV CHARACTERISTIC CURVE AND POWER CURVE

The output current versus the output voltage of GaAs PV array is represented in Fig. 8. Although the temperature of GaAs PV array increases, the output voltage will decrease while the output current increases at a higher rate. The overall effect of this change will lead to a drop in the output power as depicted in Fig. 5.60.

VI. 2 PV PARAMETERIC ANALYSIS

The effect of temperature on the solar array short circuit current is illustrated in Fig. 10. I_{Sc} is linearly proportional the temperature which nearly about 18.05 A to 18.75 A. The slight increase in I_{Sc} can be neglected.

The open circuit voltage, the maximum output power, the fill factor, and the maximum conversion efficiency versus the operating temperature are shown in fig. 11 to Fig. 14 respectively. V_{oc} is inversely proportional to the operating temperature. Its value is about 33.4 V at 10 ^{0}C down to 29.9 V at 70 ^{0}C. the maximum output power is nearly 485 W at 10 ^{0}C down to 430 W at 70 ^OC. The fill factor is about 0.805 at 10 ^{0}C down to 0.75 at 70 ^{0}C. the conversion efficiency is nearly 9.7 % at 10 ^{0}C down to 8.6 % at 70 ^{0}C.

From all previous results, for GaAs, the short circuit current increases nearly 0.064 %/ ^{0}C while the open circuit voltage, the maximum output power, the fill factor, and the efficiency decreases 0.17 %/ ^{0}C, 0.19 %/ ^{0}C , 0.11 %/ ^{0}C and 0.19 %/ ^{0}C respectively.

VII. CONCLUSION

Sizing of the GaAs photovoltaic array of UASat is calculated where the area of the solar array is equal nearly 3.77 m^2 and the solar array mass nearly 17.5 Kg are obtained. The number of series cells and the number of parallel strings are 32 and 12 respectively. While, the NiCd secondary battery is selected for LEO orbit operation where, UASat used one NiCd battery capacity. The NiCd Battery mass is equal 27.5 Wh and 20.7 Kg respectively. From the study of the effect of the solar insolation on GaAs solar array of UASat, The efficiency of GaAs solar array increased with the solar intensity which about 8.6 % at 250 W/m^2 up to 9.1 % at 1350 W/m^2.

It is clearly that GaAs solar array fill factor degraded with the temperature about 0.805 at 10 ^{0}C down to 0.75 at 70 ^{0}C. The conversion efficiency is nearly 9.7 % at 10 ^{0}C down to 8.6 % at 70 ^{0}C. Therefore, it is preferred low temperature operation for space applications because it gives high performance for the solar array.

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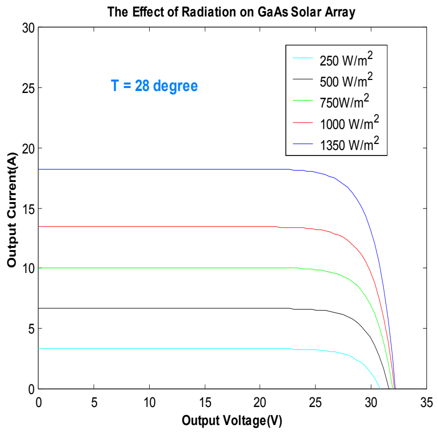

Fig. 1 the effect of solar intensity on the IV characteristics of UASat GaAs Solar array.

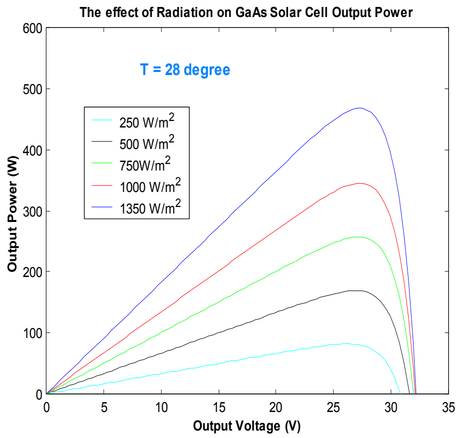

Fig. 2 the effect of solar intensity on the output power of UASat GaAs Solar array.

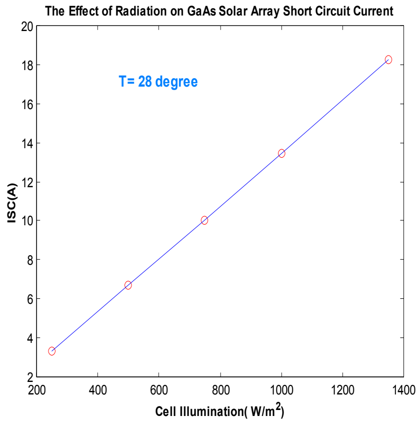

Fig. 3 the effect of solar intensity on the short circuit current of UASat GaAs Solar array.

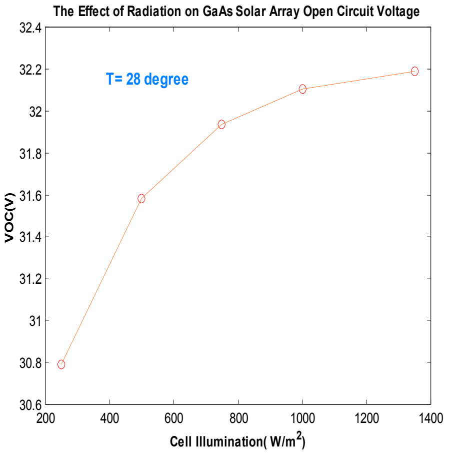

Fig. 4 the effect of solar intensity on the open circuit voltage of UASat GaAs Solar array.

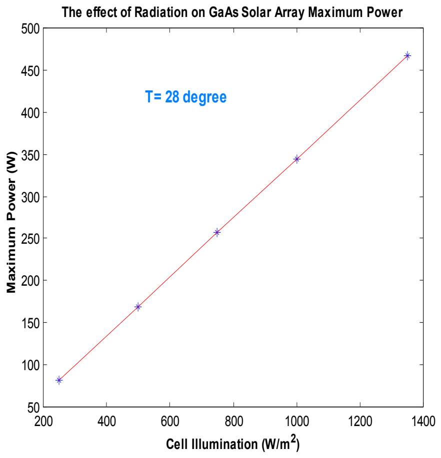

Fig. 5 the effect of solar intensity on the maximum output power of UASat GaAs Solar array.

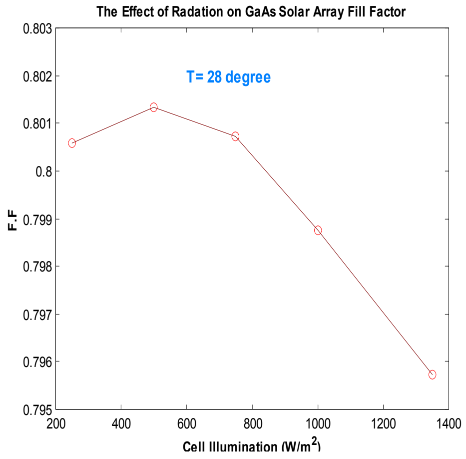

Fig. 6 the effect of solar intensity on the fill factor of UASat GaAs Solar array.

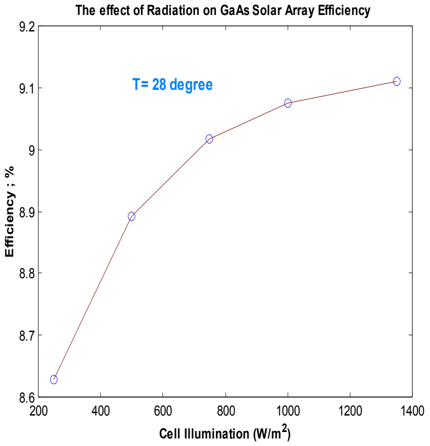

Fig. 7 the effect of solar intensity on the efficiency of UASat GaAs Solar array.

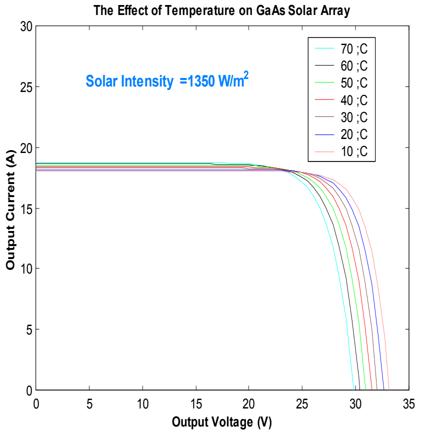

Fig. 8 the effect of temperature on the IV characteristic of UASat GaAs Solar array.

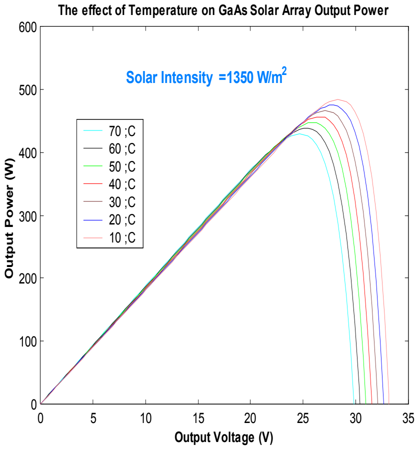

Fig. 9 the effect of temperature on the output power of UASat GaAs Solar array.

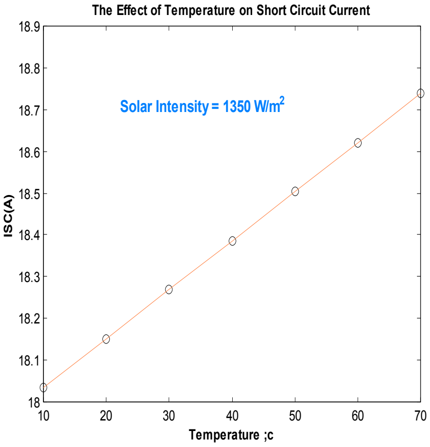

Fig. 10 the effect of temperature on the short circuit current of UASat GaAs Solar array.

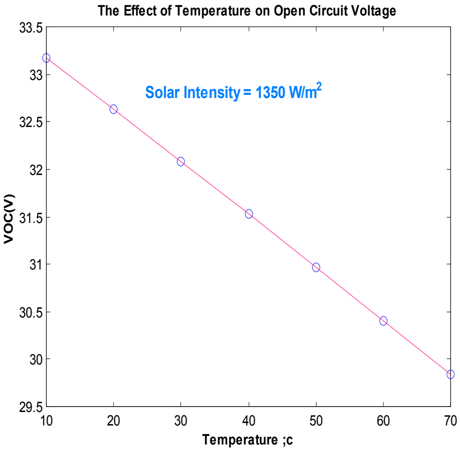

Fig. 11 the effect of temperature on the open circuit voltage of UASat GaAs Solar array.

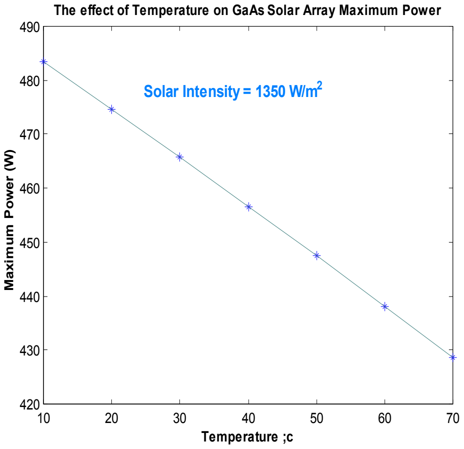

Fig. 12 the effect of temperature on the maximum output power of UASat GaAs Solar array.

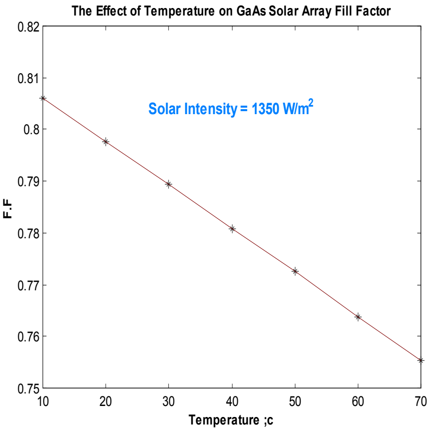

Fig. 13 the effect of temperature on the fill factor of UASat GaAs Solar array.

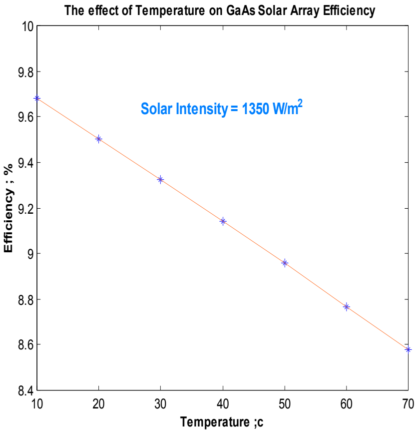

Fig. 14 the effect of temperature on the efficiency of UASat GaAs Solar array.