10th Annual Cubesat Developer’s Workshop

Design optimization of a Solar Panel Angle and its Application to CubeSat 'CADRE'

Dae Young Lee, James W. Cutler

AEROSPACE ENGINEERING
UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

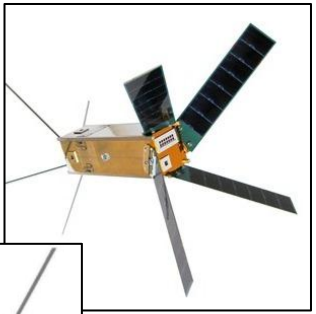
MICHIGAN EXPLORATION LABORATORY

Introduction

- Many CubeSats are power constrained.
  - There is not enough space for the solar cell installation.
  - Low Earth Orbits have varying eclipse times.

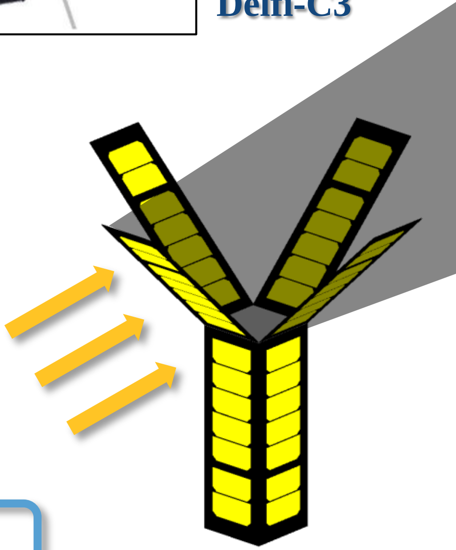
- Existing solutions
  - Deployable panels : ex. 'Space-dart' configuration

Delfi-NEXT



Delfi-C3

- Question : How can we maximize the utility of deployable panels?
  - What is the best pointing angle for the panels?
    - Anigstein et al[1]. developed a optimal pointing angle decision methodology.
    - But they assumed no shadow on panels.
  - How do you assess the impact of solar panel shadow?
    - Consideration of the shadow effect is important during the satellite design.
    - More deployable panel can cast more shadows.



CADRE

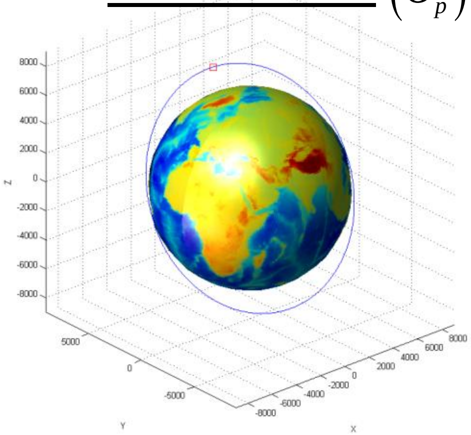
- **Goal : To develop a process that determines static solar panel angles for optimal power generation**

[1]"Analysis of Solar Panel Orientation in Low Altitude Satellites" IEEE Transactions on Aerospace and Electronic Systems VOL. 34, NO. 2 APRIL 1998

Objective Function Candidates

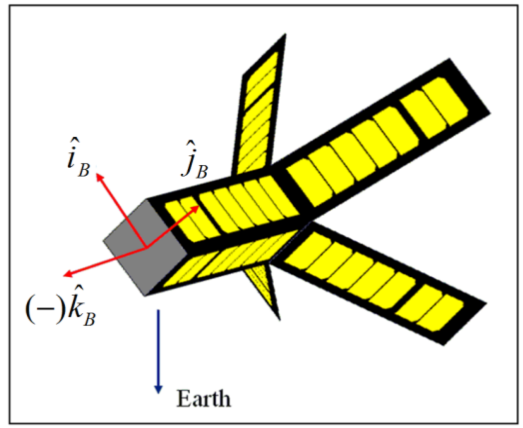
- **Problem : What is the best panel angle in the given orbit parameter**

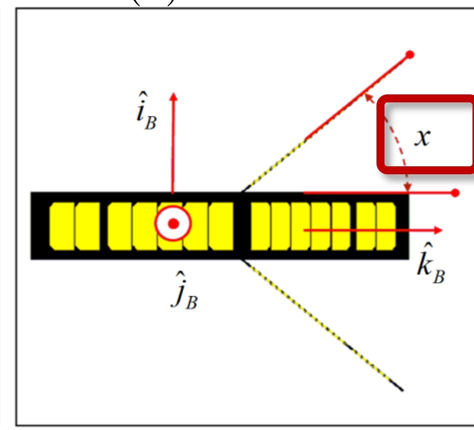
Orbit Parameter $\left(O_p\right)$



+

Design variable $\left(x\right)$





- **There are multiple objective functions for the power generation optimization**

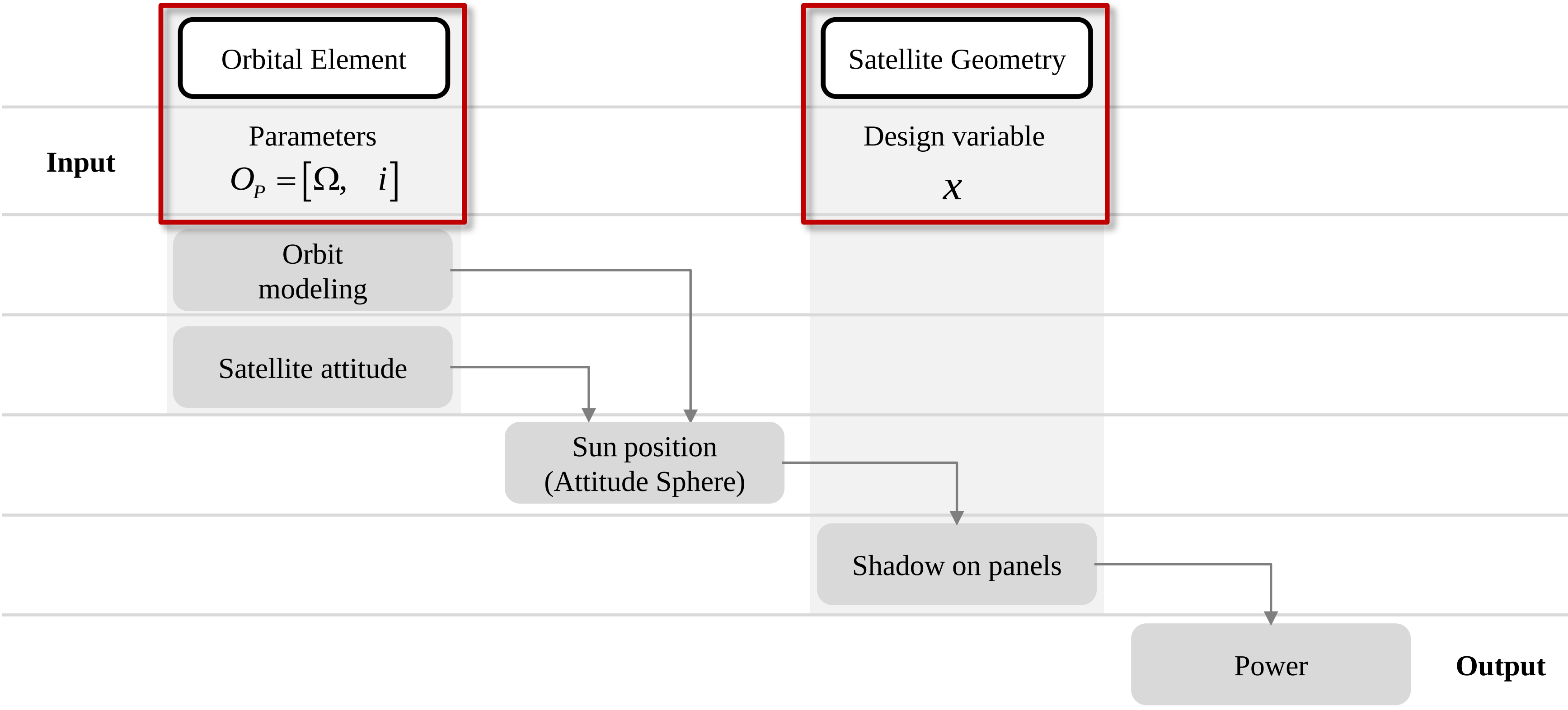
$$\max\left\{\int_0^T P\left(x, O_p, t\right)dt,\ T = 1\ \text{year}\right\}$$ - Maximization of the total power generated during 1 year period

$$\max\left\{\min\left\{\frac{1}{T}\int_{(n-1)T}^{nT} P\left(x, O_p, t\right)dt,\ T = 1\ \text{orbit},\ n \in \left[0 \quad \frac{1\ \text{year}}{T}\right]\right\}\right\}$$ - Maximization of the minimum orbit average power which was recorded during 1 year simulation period

$$\max\left\{\min\left\{P\left(x, O_p, t\right), t \in \left[0, T_{orbit}\right]\right\}\right\}$$ - Maximization of the low limit power generated during 1 orbit period (Sun synchronous Orbit)

Simulation Process

- **Simulation Process for the power evaluation**



$$P\left(x, O_p, t\right)(\text{watt})$$

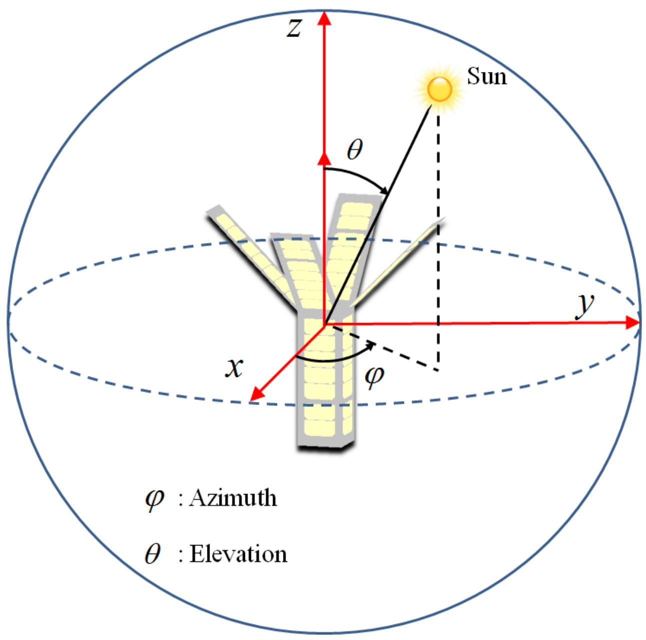
- **Sun position mapping in the attitude sphere[2] can be done based on the simulation**

Orbit Dynamics **Attitude Dynamics**

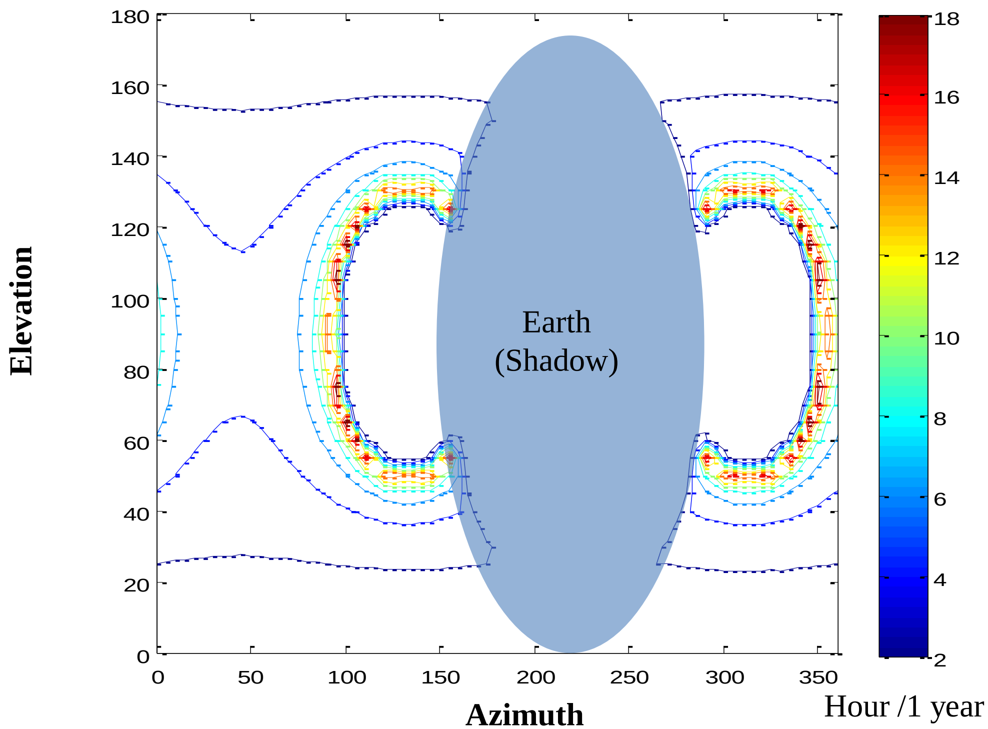
$$\vec{S}\Big|_B(t) = \overline{O_{B/I}}(t)\cdot\underline{\vec{S}\Big|_I(t)} = \begin{bmatrix}\varphi(t) & \theta(t) & \rho\end{bmatrix}$$

Sun Simulation

Ex) Inc = 60 °, RAAN = 90 °
03/20/2015 ~ 03/19/2016



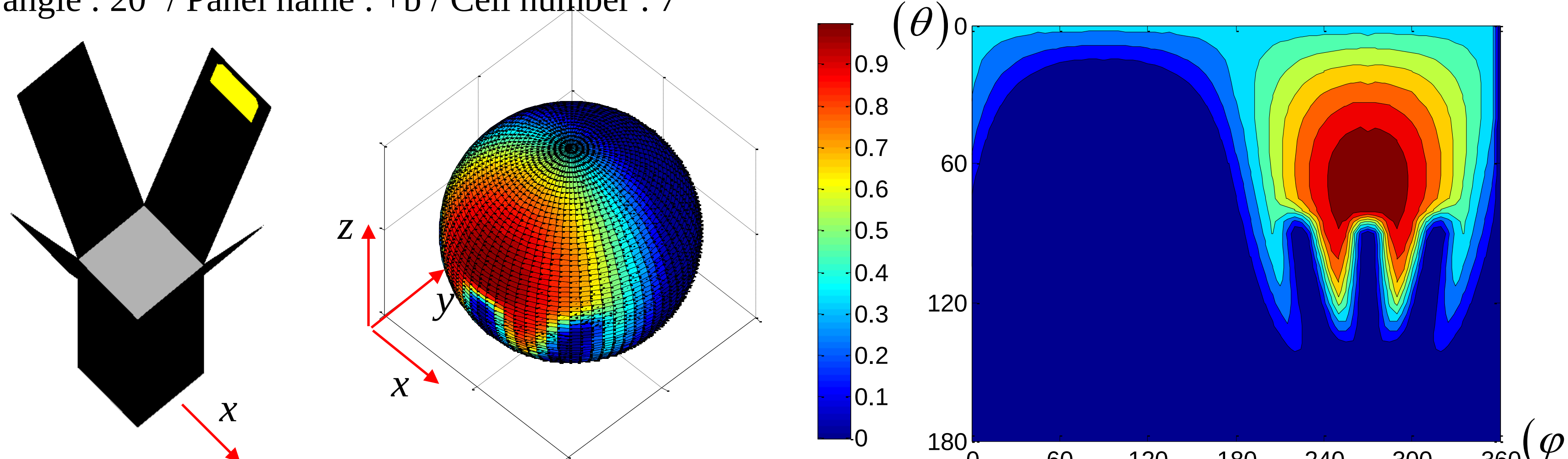
Attitude Sphere[2]



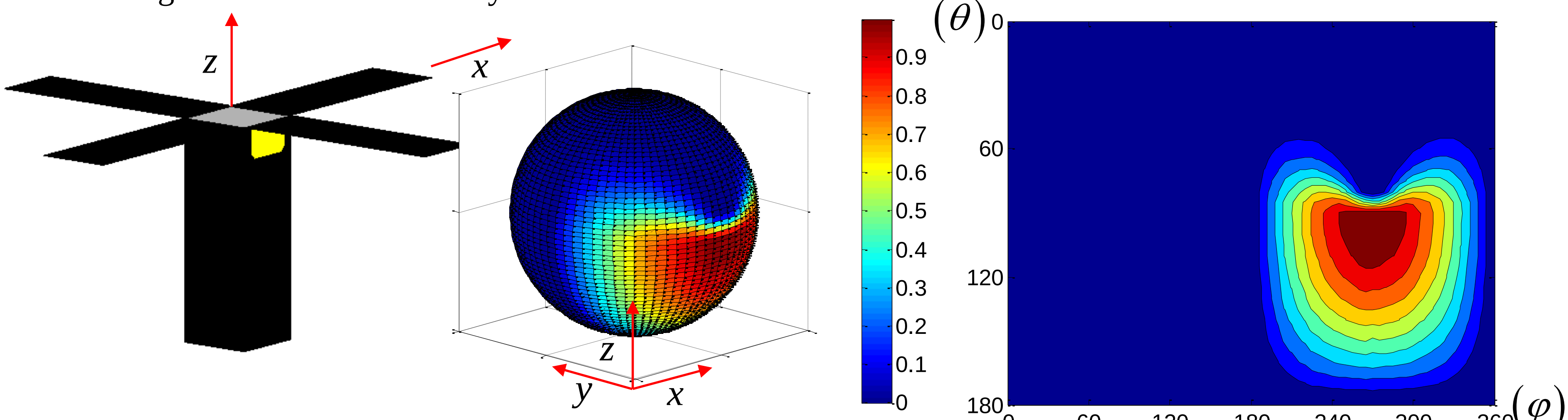
[2] J.C. Springmann and J.W. Cutler "Optimization of Directional Sensor Orientation with Application to Photodiodes for Spacecraft Attitude Determination", Proceedings of the 23rd AAS/AIAA Spaceflight Mechanics Meeting, Kauai, Hawaii, February 2013.

- **We calculate the solar cell surface area projected in the direction of the Sun**
  - **Using OpenGL , we calculate the area quickly and make a database .**

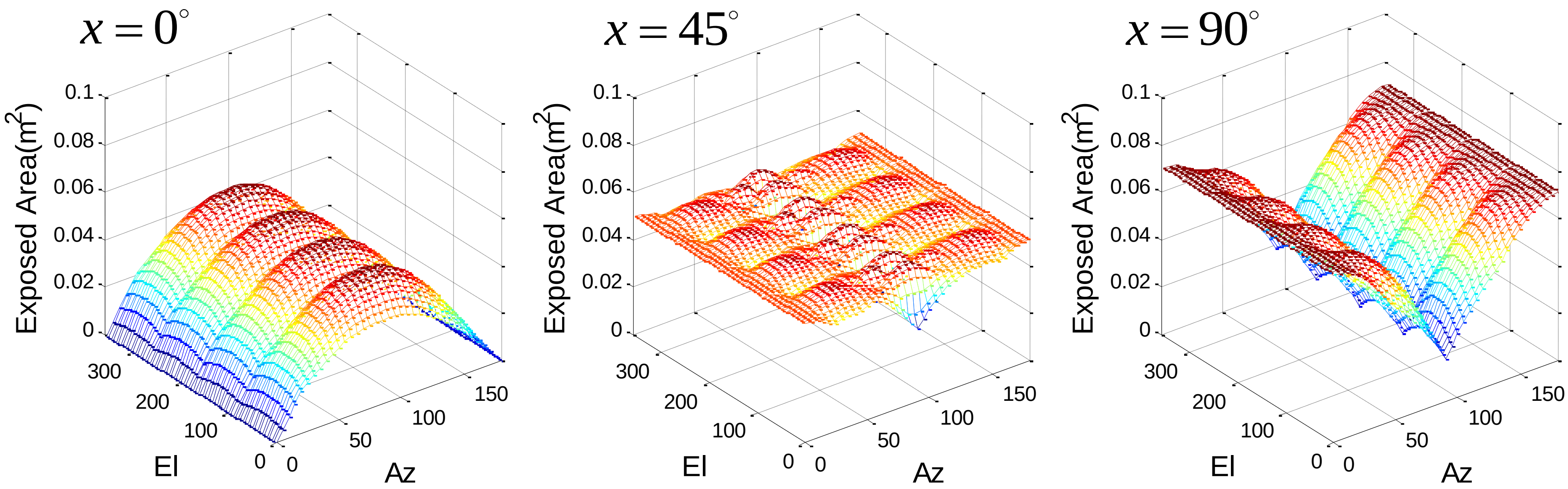
Panel angle : 20˚ / Panel name : +b / Cell number : 7



Panel angle : 90˚ / Panel name : -y / Cell number : 1



- **Sum of each cell's projected area in the attitude sphere**



- **We use a following equation to calculate the generated power by solar cells**

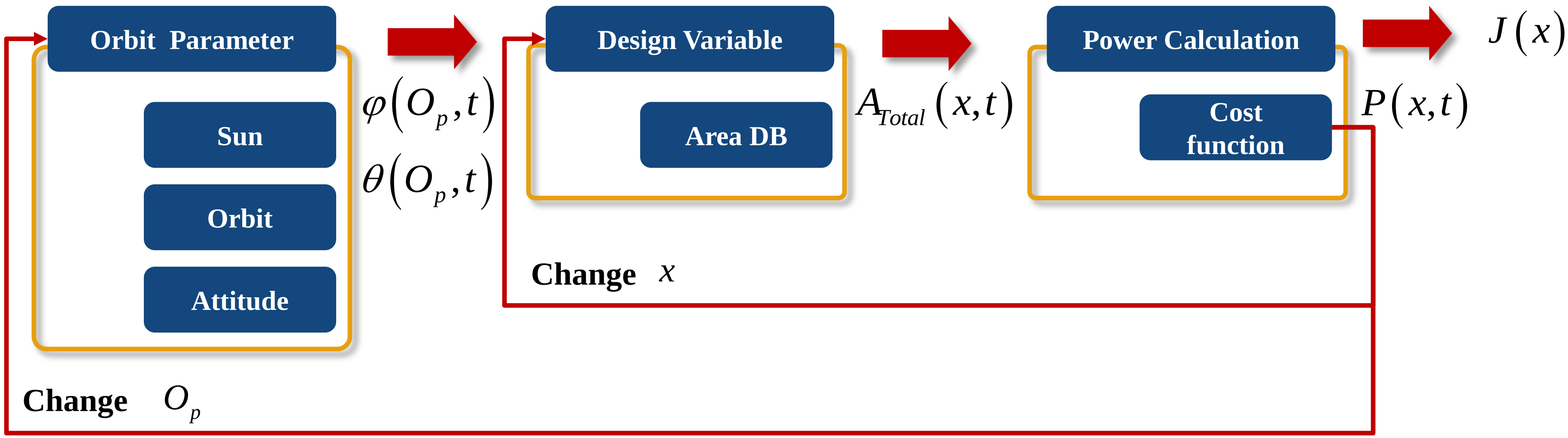
$$P\left(x, O_p, t\right) = S_0 \cdot \varepsilon \cdot \sum_{i=1}^{12} \sum_{j=1}^{7} A_{i,j}\left(x, \varphi_{sun}(O_p, t), \theta_{sun}(O_p, t)\right)$$

$$= S_0 \cdot \varepsilon \cdot A_{Total}\left(x, \varphi_{sun}(O_p, t), \theta_{sun}(O_p, t)\right)$$

$$S_0 \simeq 1366 \mathrm{W/m^2}, \ \varepsilon \simeq 28\% \qquad 0^\circ \le x \le 90^\circ, \ 0^\circ \le \varphi_{sun}(O_p, t) < 360^\circ, \ 0^\circ \le \theta_{sun}(O_p, t) \le 180^\circ$$

  – **It is assumed that solar power generation is proportional to the solar cell surface area projected in the direction of the Sun.**

- **Panel angle value can be found out by exhaustive search on design space**

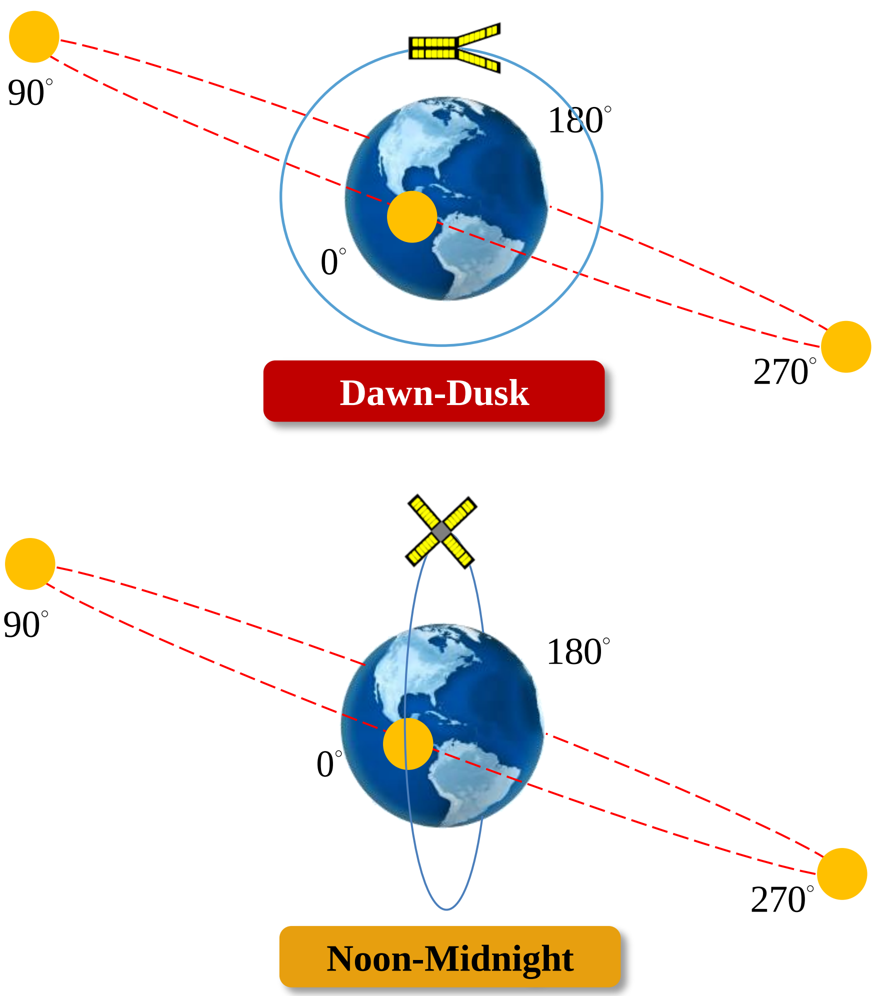


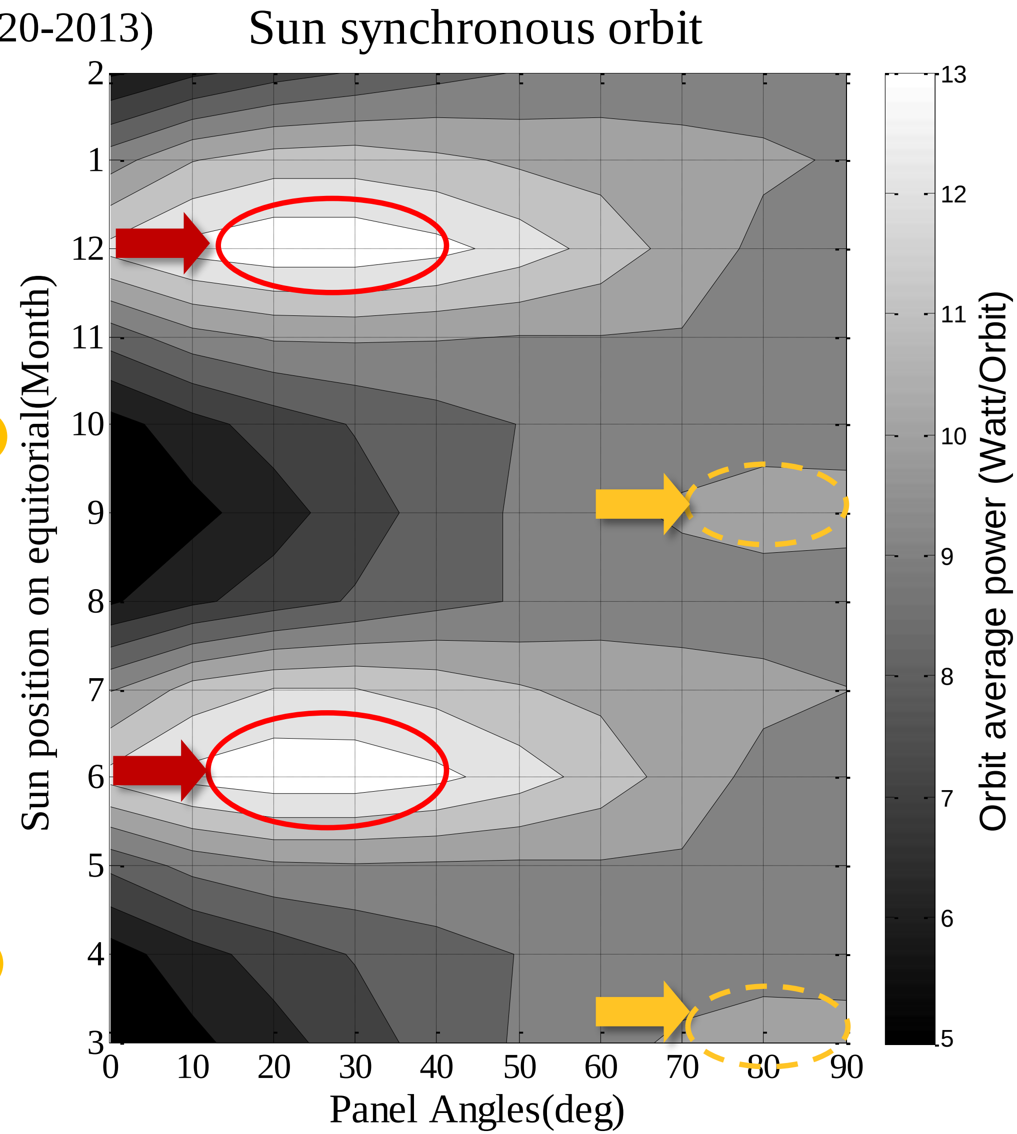
$$O_p = \begin{bmatrix} e \\ a \\ i \\ \Omega \\ \omega \\ \upsilon \end{bmatrix} \Rightarrow \begin{bmatrix} i \\ \Omega \end{bmatrix}$$

- In this exhaustive searching process, the range of the panel angle x is 0°, 3 °, 6 °, …, 90 °
- the major parameters which affect solar power generation are the inclination(i) and RAAN(Ω)
  - Because, the Sun incident angle to orbital plane is decided by the inclination(i) and RAAN(Ω)
- The calculation speed is accelerated with MATLAB/Simulink coder and OpenGL
  - Area calculation with OpenGL : 1 DB generation takes about 4 min.
  - 1 year simulation with 10 second time interval takes about 5 min

Panel angle optimization of the Sun-synchronous orbit

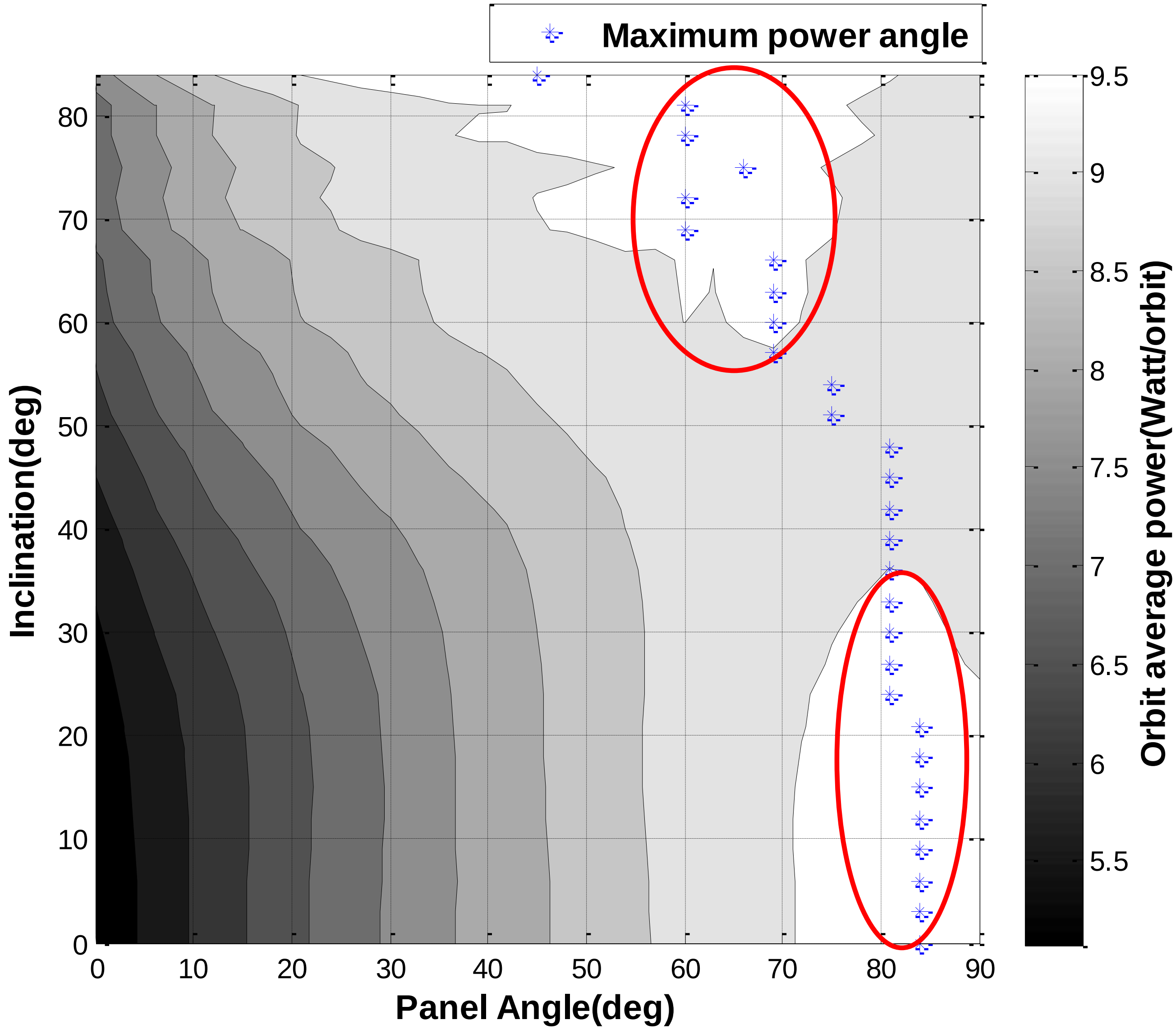
(Altitude : 700km, Inclination : 98˚, Launch :3-20-2013)





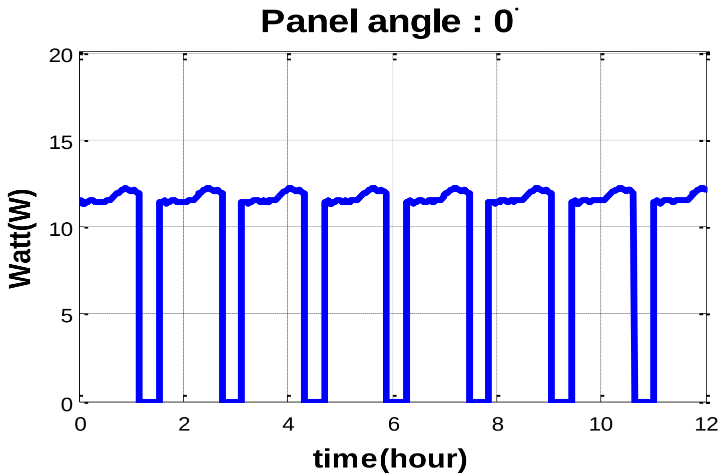
Panel angle optimization of the Non Sun-synchronous orbit

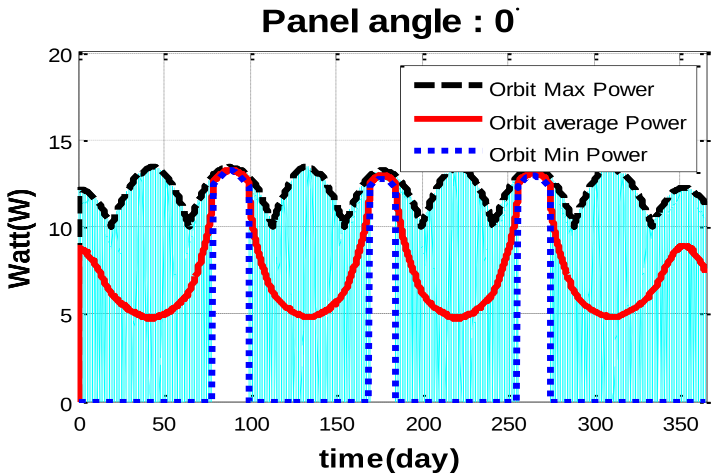
- Panel angle : 0 ˚ ~ 90˚
- Inclination : 0 ˚ ~ 82˚
- In the given inclination range, the moving speed of RAAN(Ω) is greater than 360˚/1year
  - Then we can rule out the RAAN(Ω) effect and compare the inclination and the panel angle's relation.

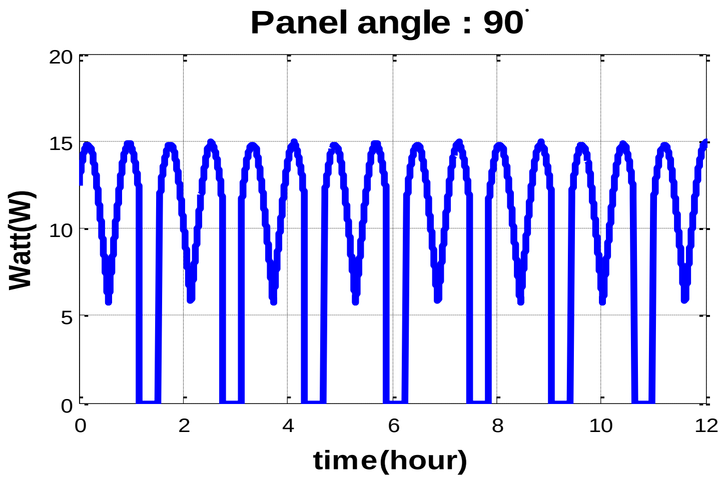


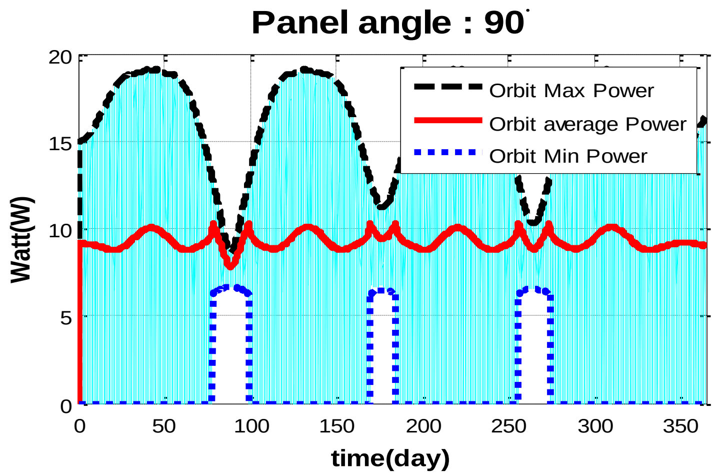
Result Analysis of Non Sun-Synchronous orbit (Inclination : 67°)

- Small panel angle has smaller daily deviation of the power than the large panel angle
- However, Large panel angle has smaller yearly deviation of the orbit average power than small panel angle



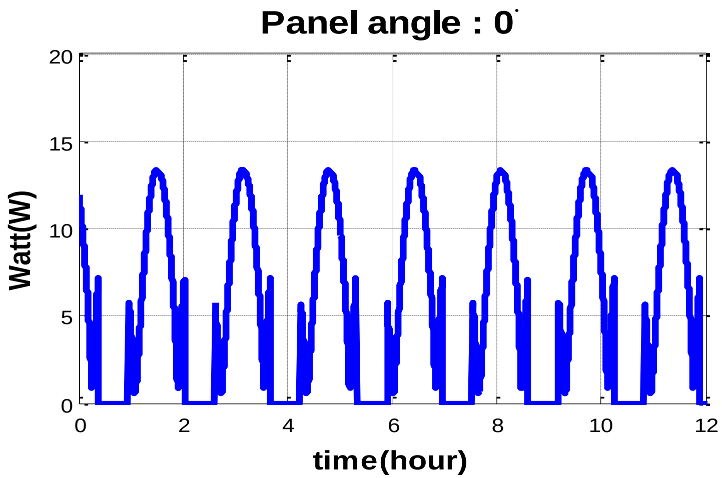


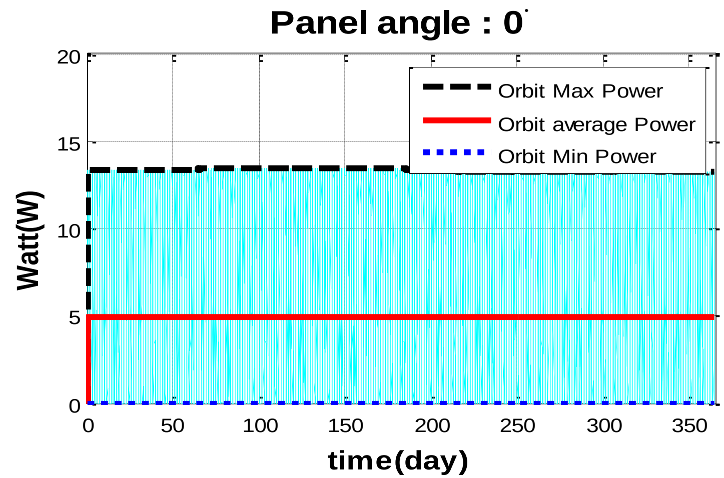


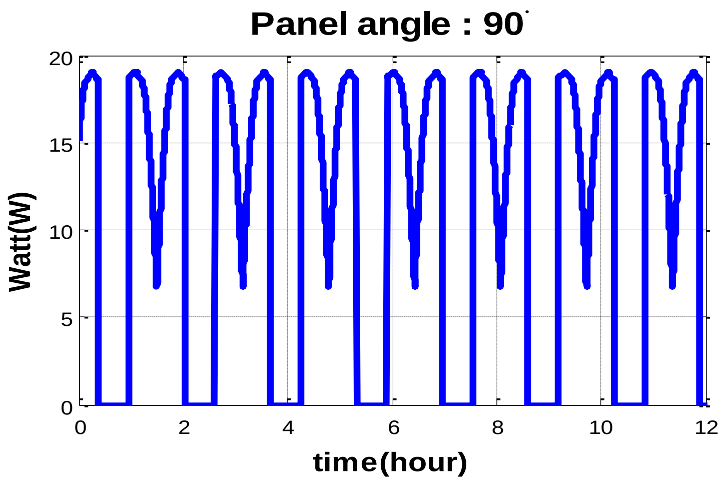


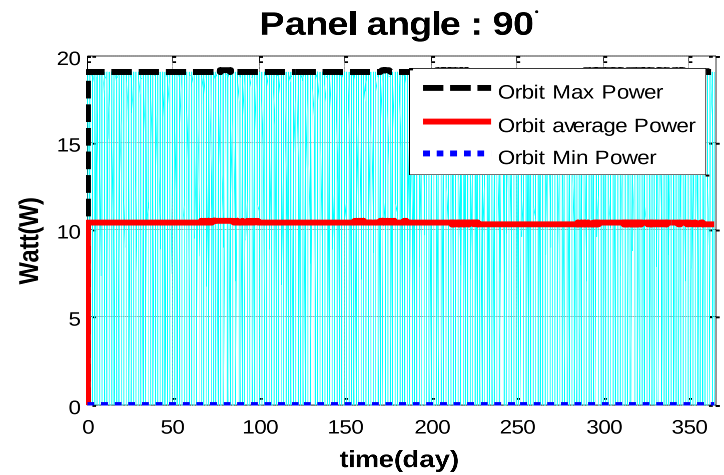
Result Analysis of Sun-Synchronous orbit ('Noon-Midnight' Orbit)

- Altitude : 700km , Inclination : 98˚, Launching date : 3-20-2015
- During 1 year, the orbit average power has no change.



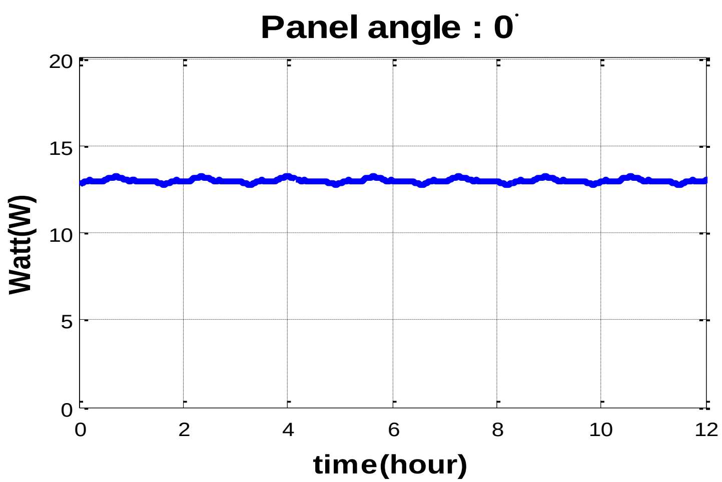


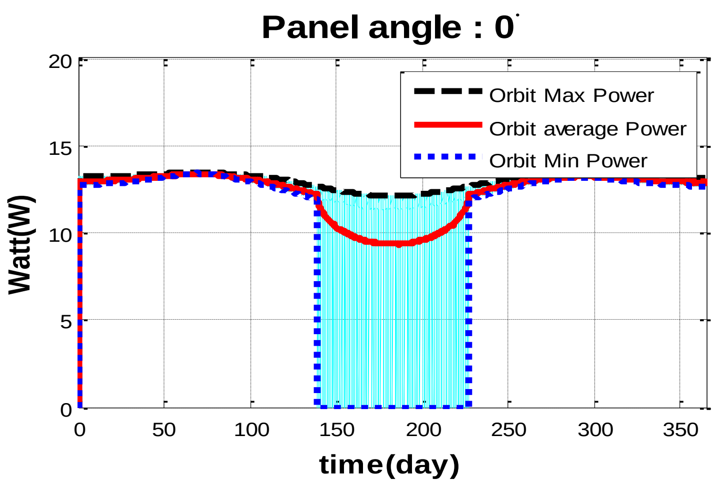


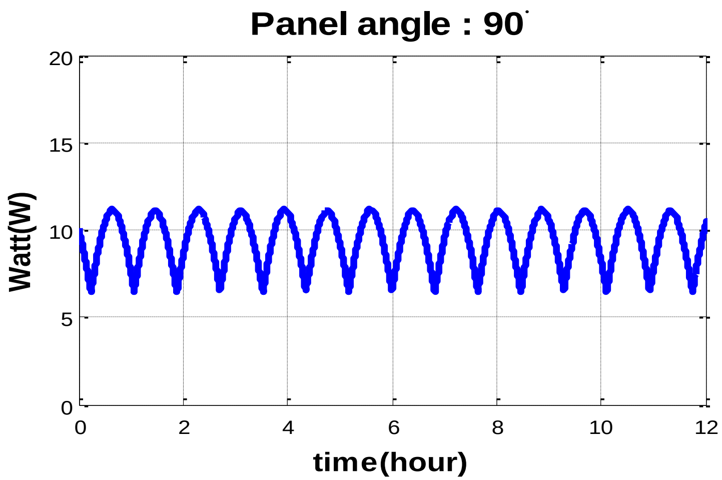


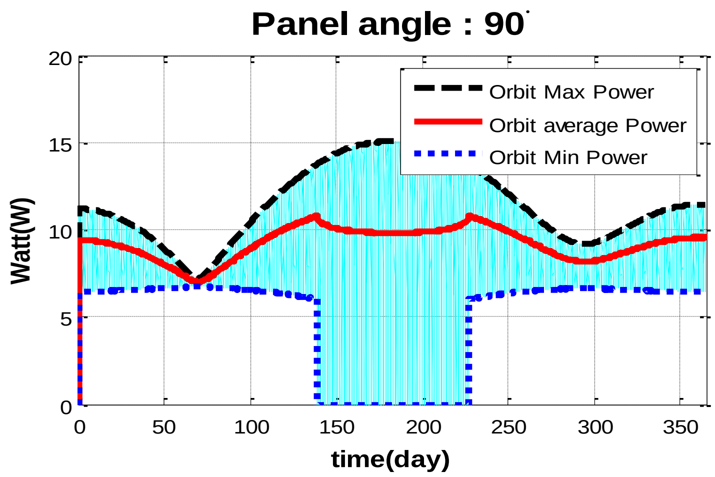
Result Analysis of Sun-Synchronous orbit ('Dawn-Dusk' Orbit)

- Altitude : 700km, Inclination : 98˚, Launching date : 6-20-2015
- If altitude is ≥ 1,060km, the eclipse period will not appear.









Conclusions

- **Advanced panel angle design optimization technique**
  - **Based on the result of the numerical simulation of every possible condition**
  - **Shadow effects consider**
    - **Deployable panels to other deployable panels**
    - **Deployable panels to the body panels**
  - **Dynamics consider**
    - **Orbit dynamics with J2, J3, J4.**
    - **Attitude dynamics**

- **Future work : EPS design optimization**
  - **Solar cell IV curve characteristic Modeling**
  - **Cell/Radiator thermal characteristics.**
  - **Battery characteristic**
  - **Albedo consideration**

- **Large scale Multidisciplinary Design Optimization(MDO) of Cubesat**
  - **Because the running all possible case simulation is very exhaustive and not practical**
  - **Researching 'Gradient based optimization'**

Large Scale Cubesat MDO