10th Annual Cubesat Developer's Workshop

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

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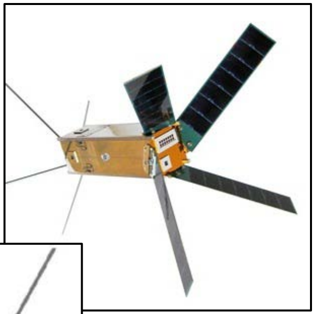
Introduction

Delfi-NEXT

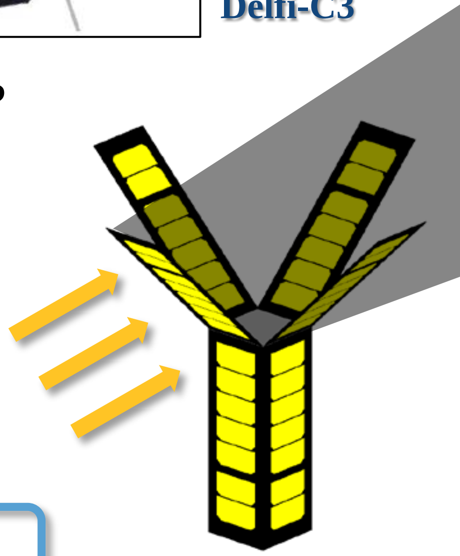


Delfi-C3

- **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**

- **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

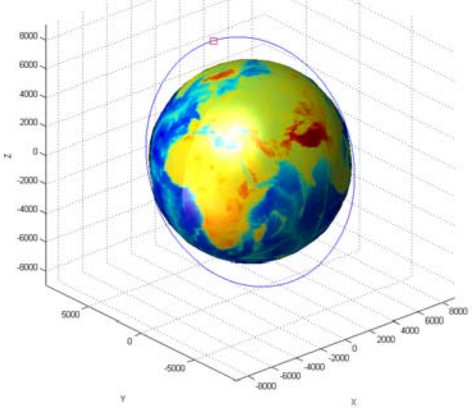
- **Goal : To develop a process that determines static solar panel angles for optimal power generation**

[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 (O_p)



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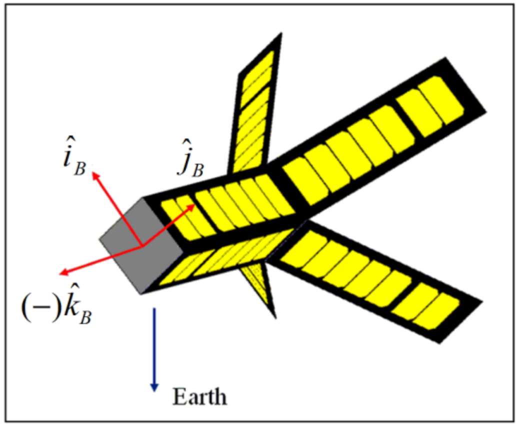
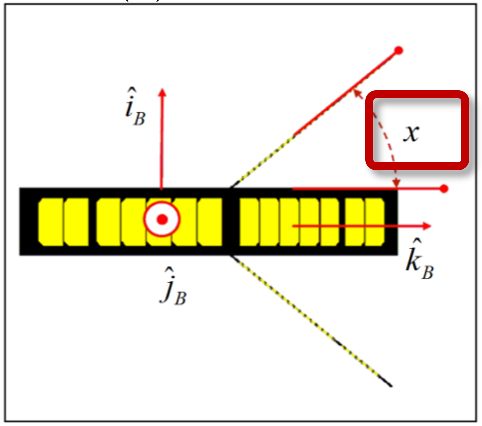
Design variable (x)





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

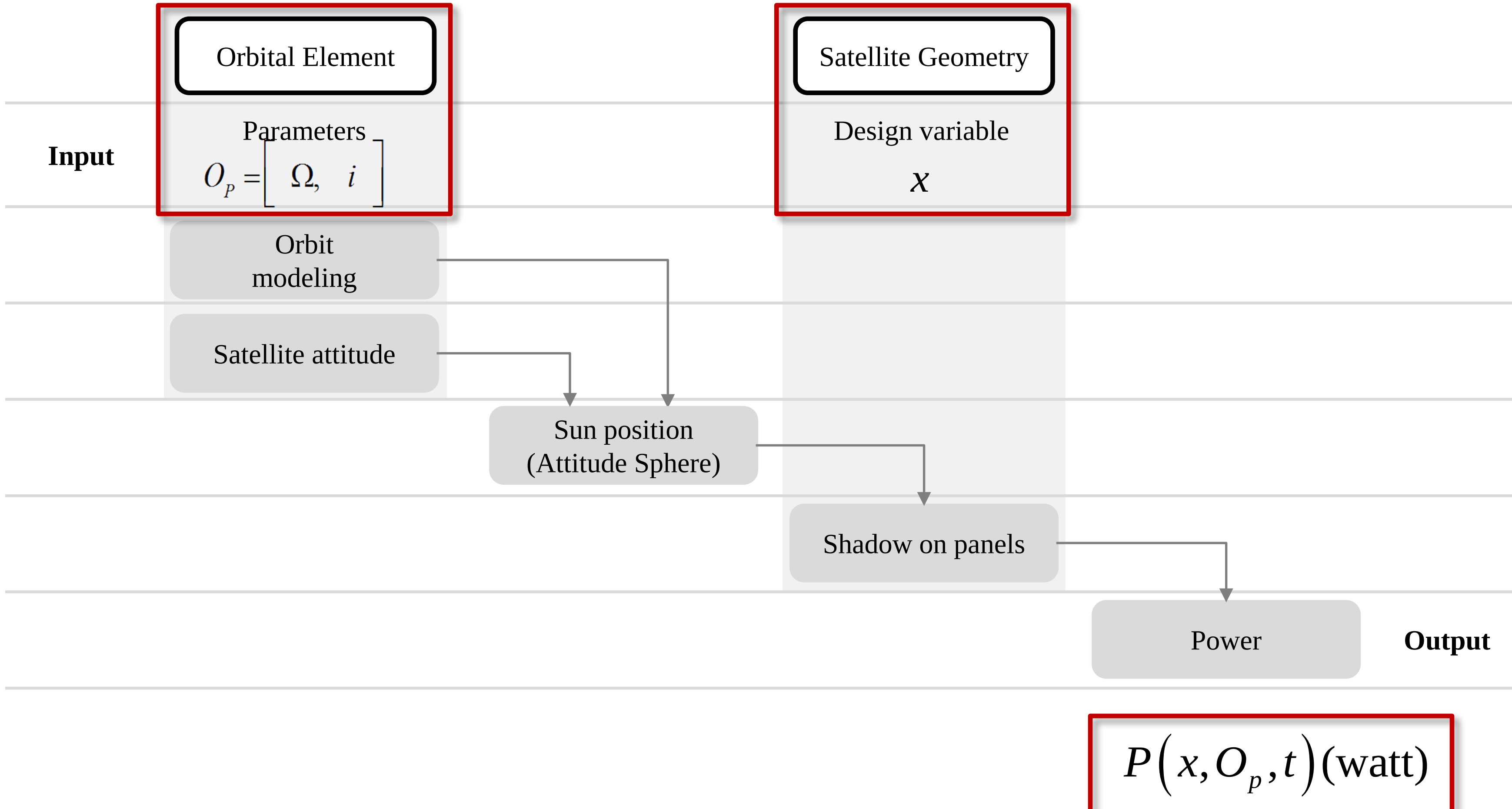
$\max\left\{\int_0^T P\left(x,O_p,t\right)dt,\ T=1\text{ year}\right\}$ - Maximization of the total power generated during 1 year period

$\max\left\{\min\left\{\frac{1}{T}\int_{(n-1)T}^{nT} P\left(x,O_p,t\right)dt,\ T=1\text{ orbit},\ n\in\left[0\quad \frac{1\text{ year}}{T}\right]\right\}\right\}$ - 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**



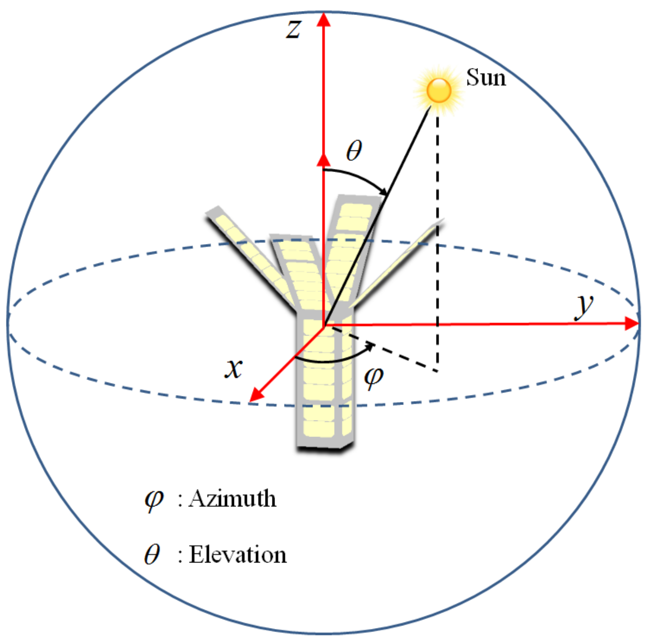
- **Sun position mapping in the attitude sphere[2] can be done based on the simulation**

Orbit Dynamics — **Attitude Dynamics**

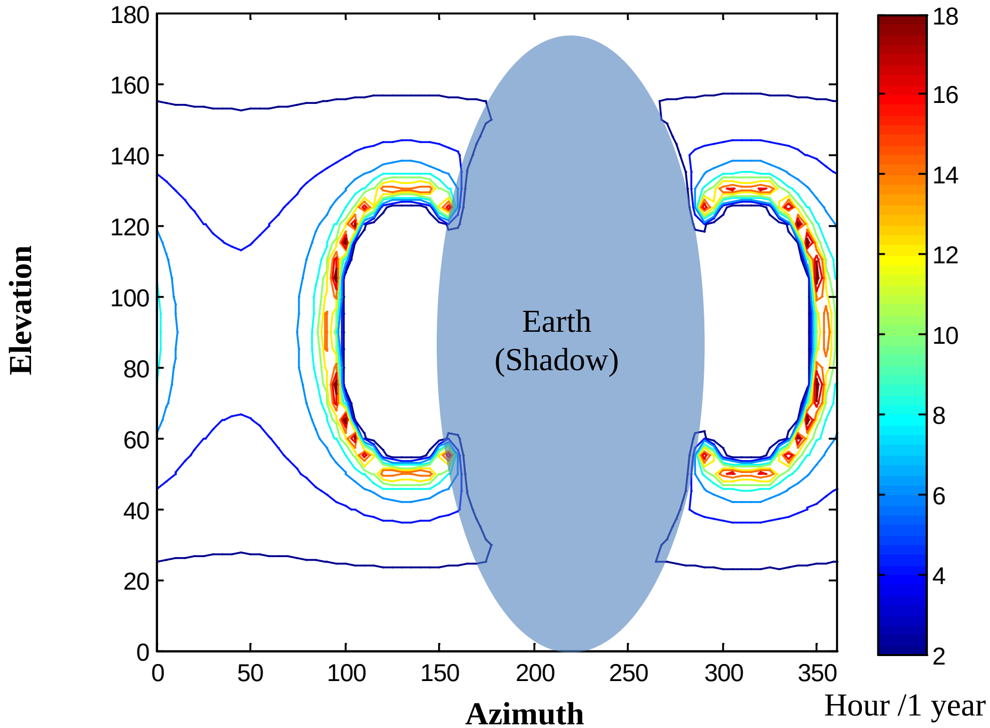
$$\vec{S}\big|_B(t) = \overline{O_{B/I}(t)} \cdot \underline{\vec{S}\big|_I(t)} = \begin{bmatrix} \varphi(t) & \theta(t) & \rho \end{bmatrix}$$

Sun Simulation

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



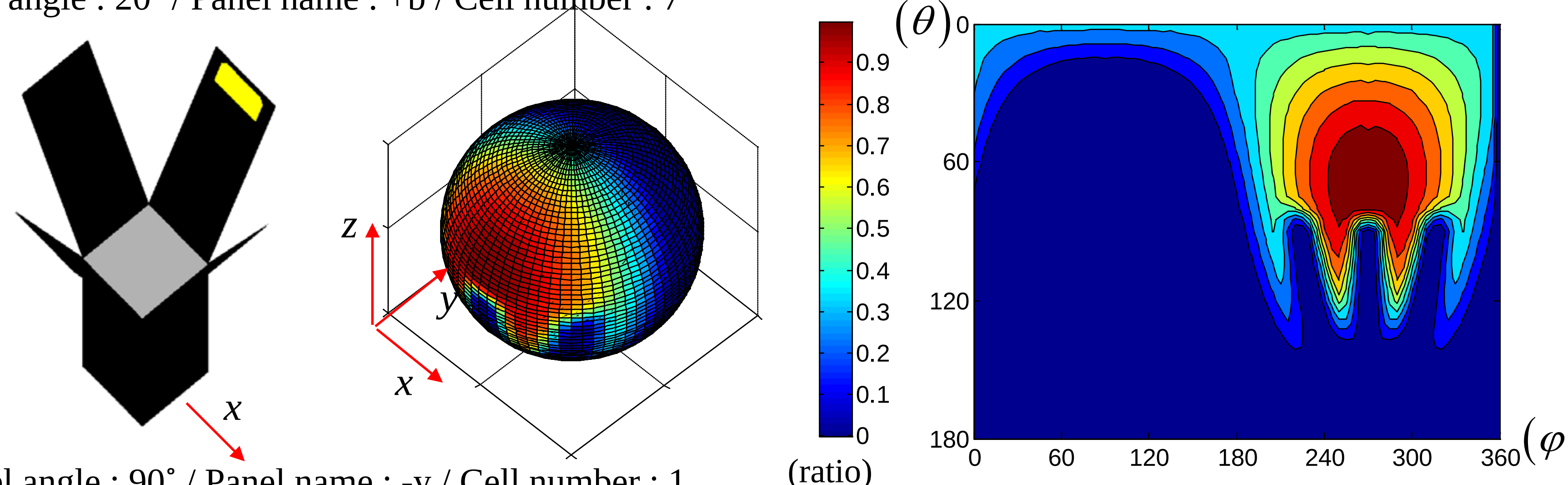
Attitude Sphere[2]



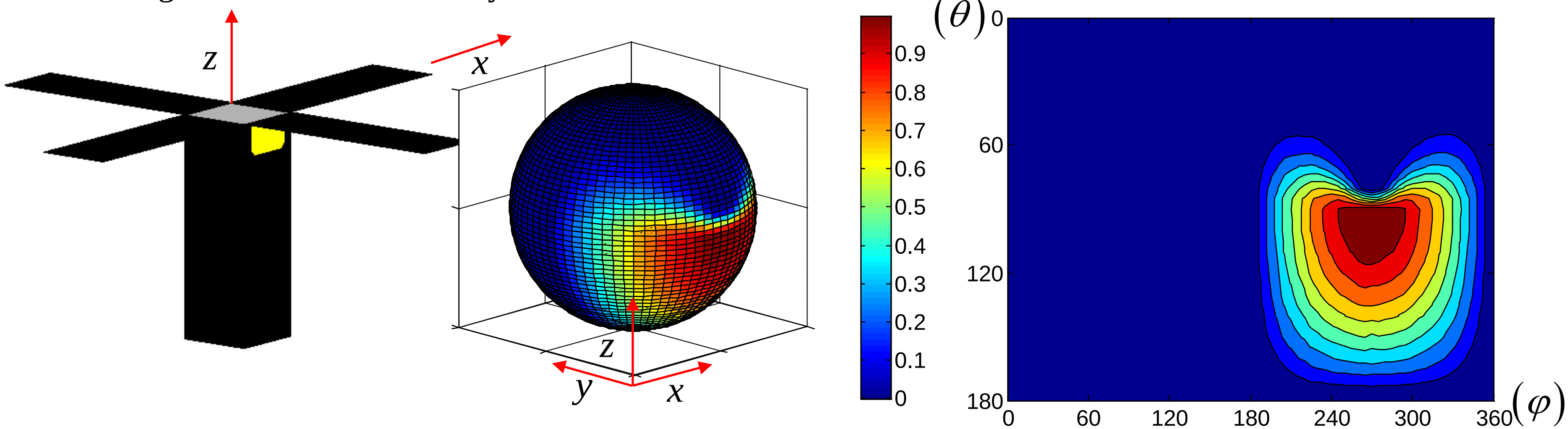
[2] J.C. Springmann and J.W. Cutler "Optimization of Directional Sensor Orientation with Application to Photodiodes for Spacecraft Attitude Determination", Proceedings of the 23rd AAS/AIAA Spaceflight Mechanics Meeting, Kauai, Hawaii, February 2013.

- **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 .**

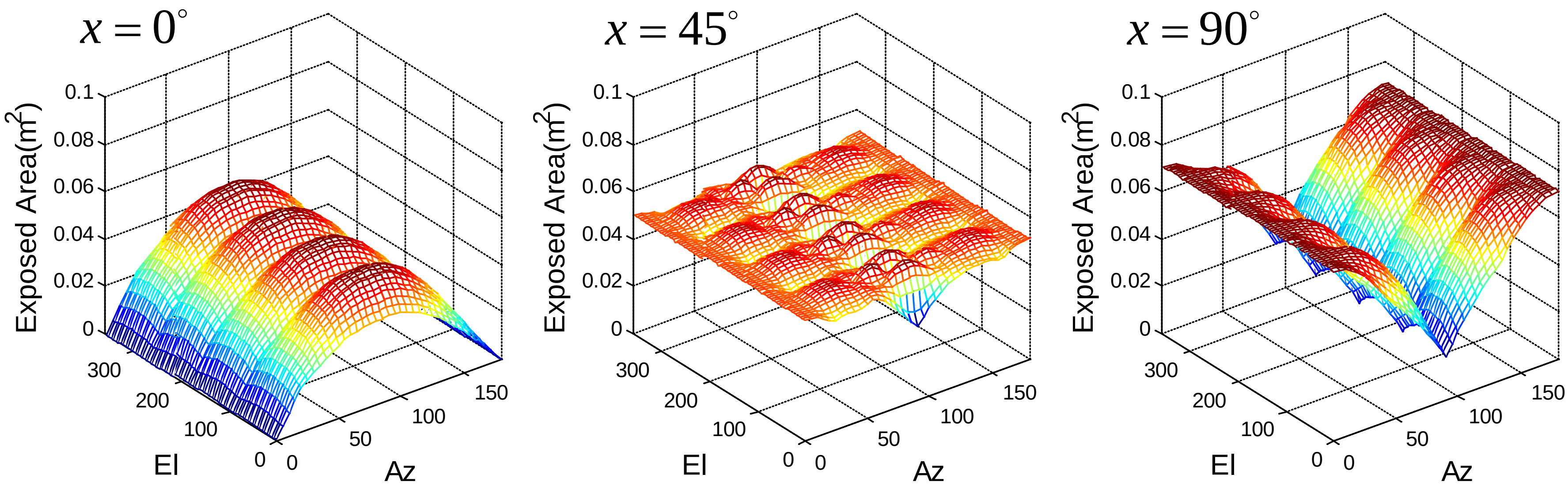
Panel angle : 20˚ / Panel name : +b / Cell number : 7



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**

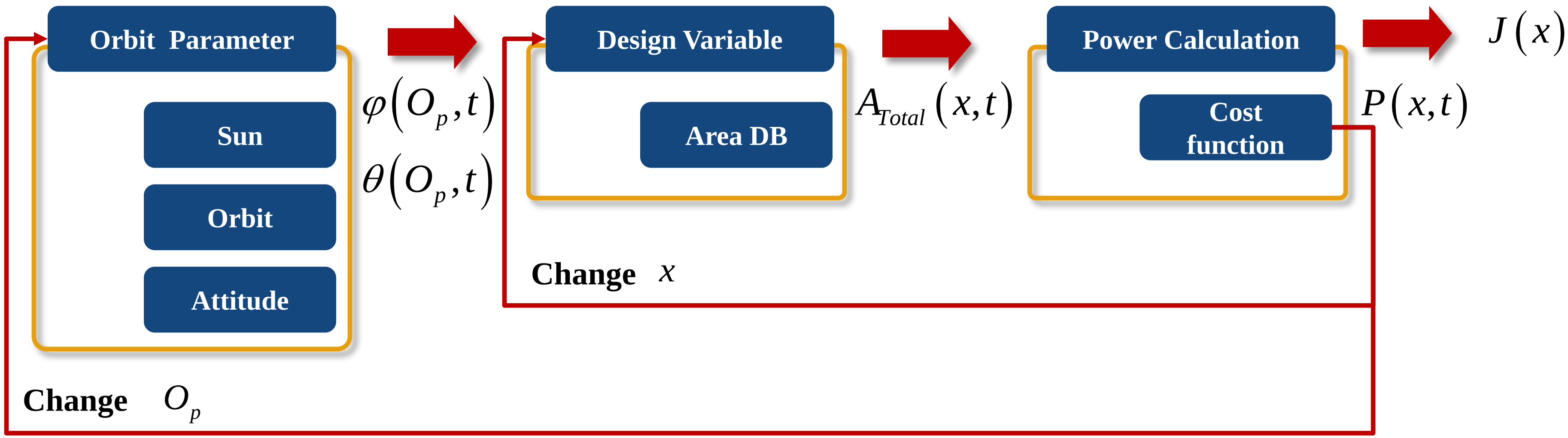
$$P\left(x,O_p,t\right)=S_0\cdot\varepsilon\cdot\sum_{i=1}^{12}\sum_{j=1}^{7}A_{i,j}\left(x,\varphi_{sun}(O_p,t),\theta_{sun}(O_p,t)\right)$$

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

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

  – **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**



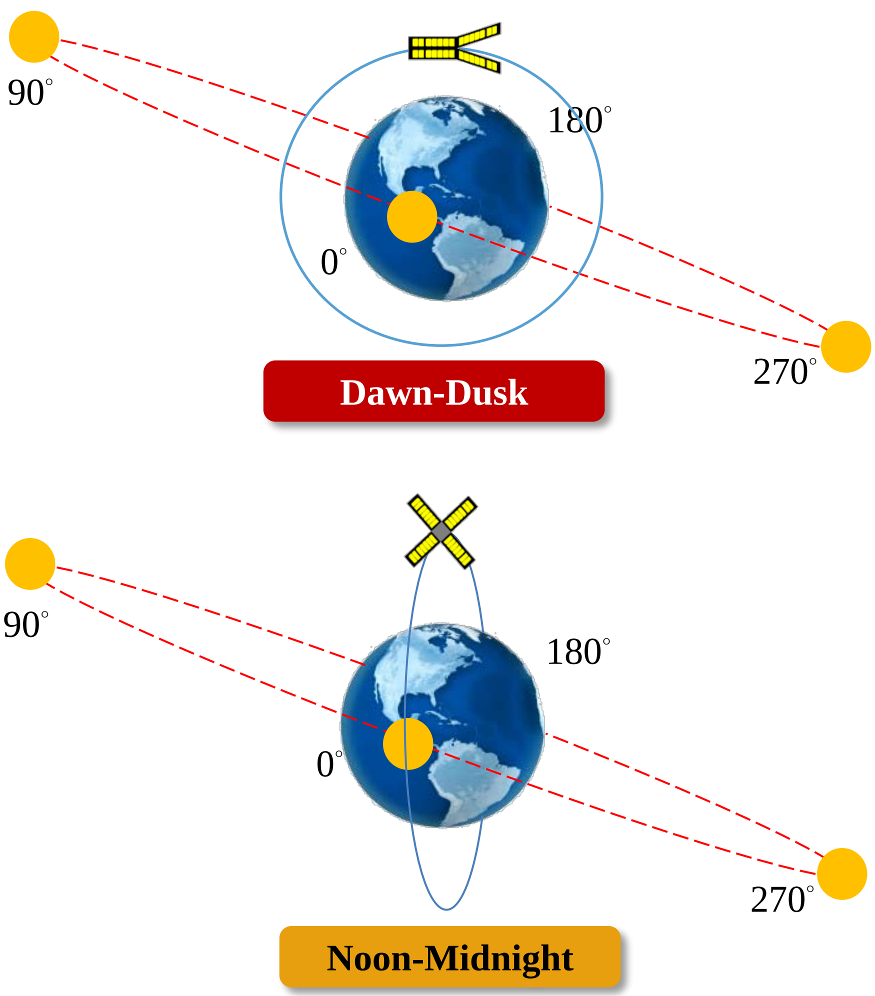
- In this exhaustive searching process, the range of the panel angle x is $0^\circ, 3^\circ, 6^\circ, \ldots, 90^\circ$

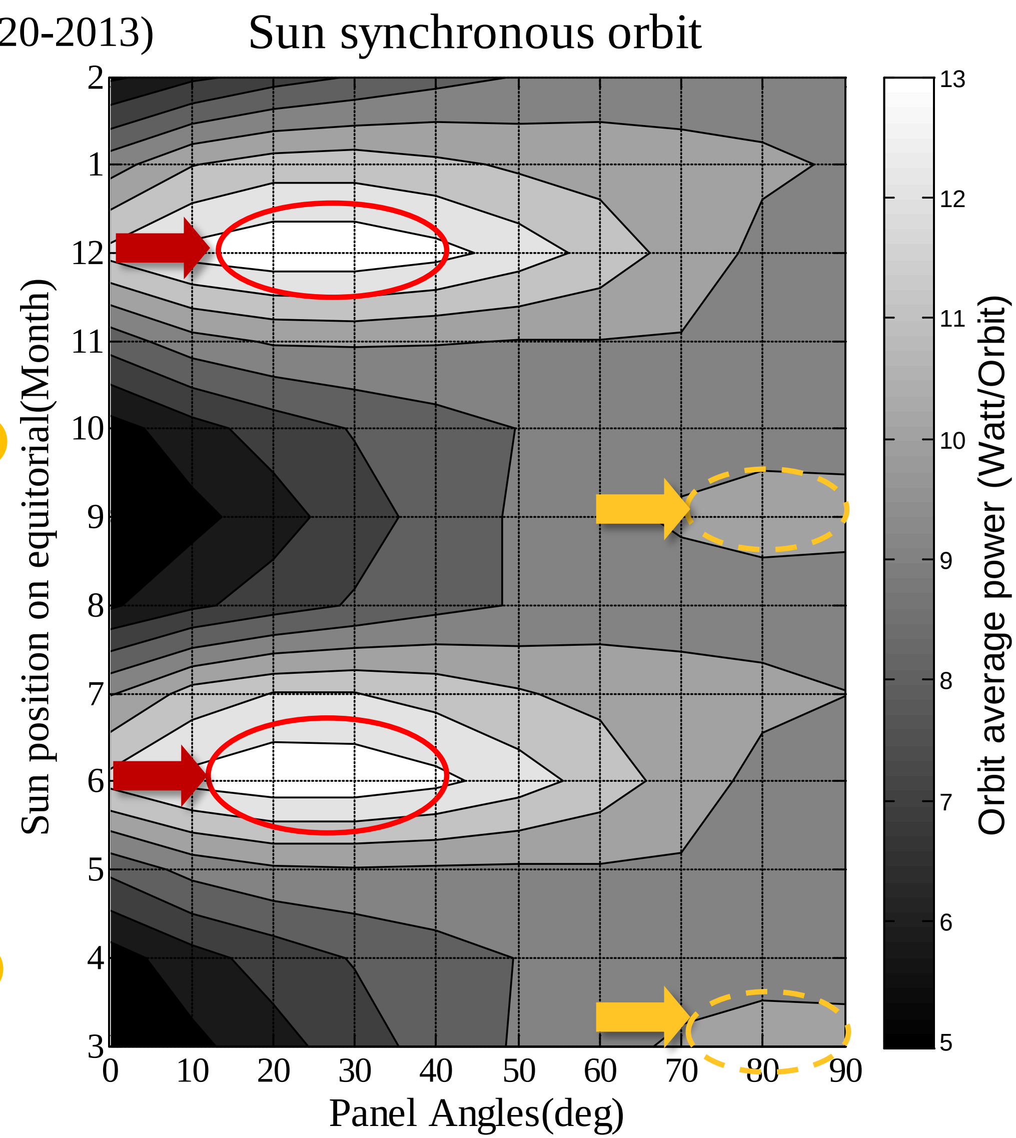
$$O_p = \begin{bmatrix} e \\ a \\ i \\ \Omega \\ \omega \\ \upsilon \end{bmatrix} \Rightarrow \begin{bmatrix} i \\ \Omega \end{bmatrix}$$

- 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

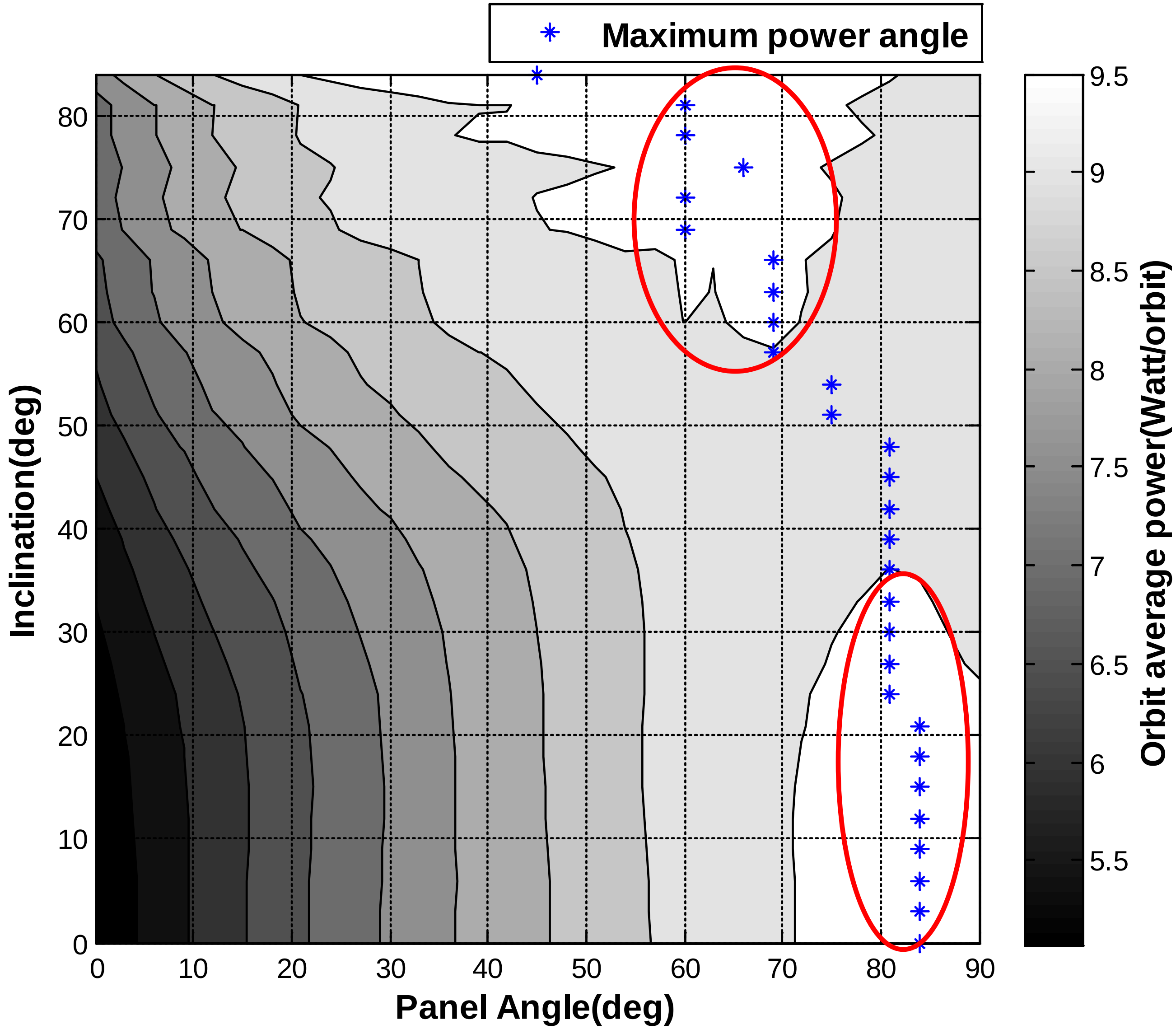
(Altitude : 700km, Inclination : 98°, Launch :3-20-2013)





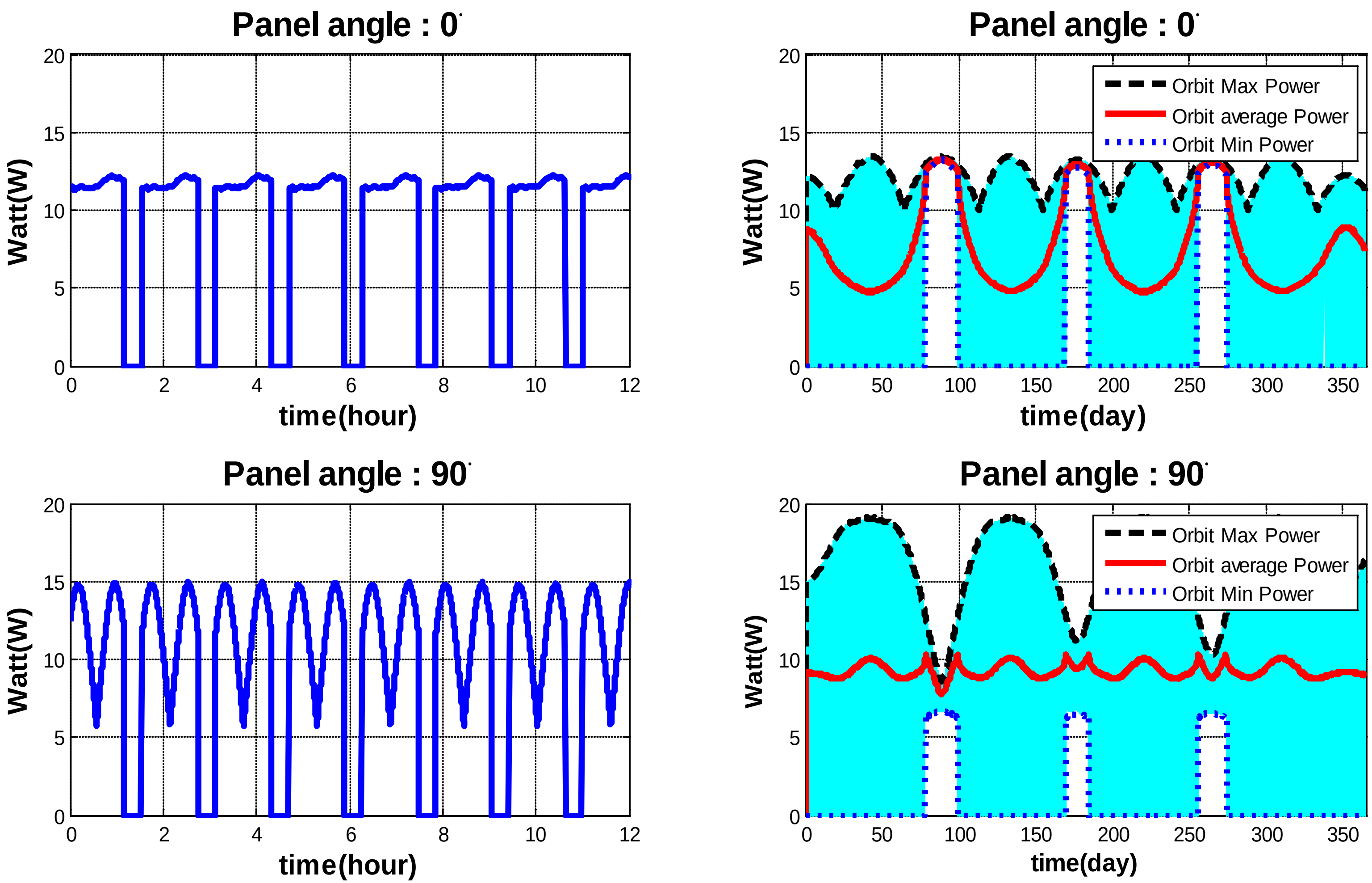
Panel angle optimization of the Non Sun-synchronous orbit

- 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.



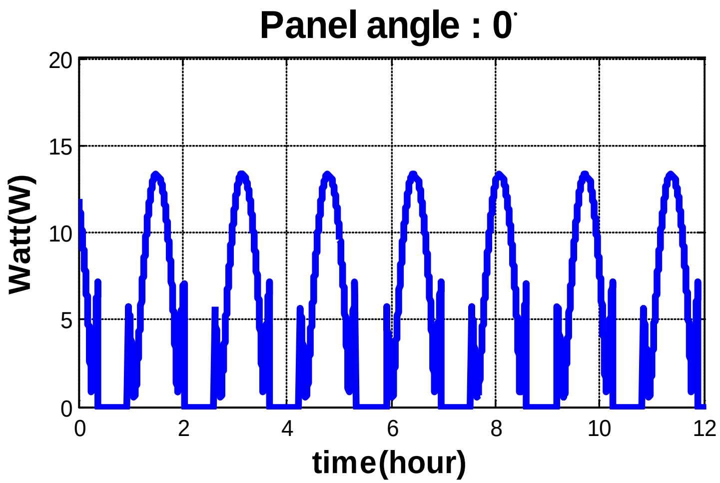
Result Analysis of Non Sun-Synchronous orbit (Inclination : 67°)

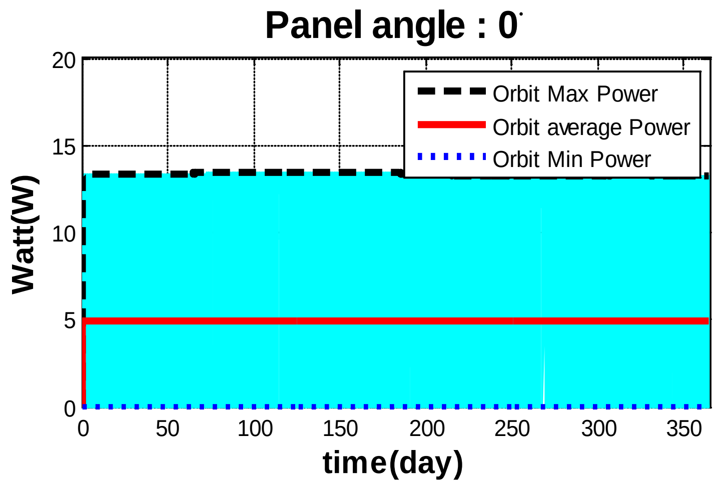
- Small panel angle has smaller daily deviation of the power than the large panel angle
- However, Large panel angle has smaller yearly deviation of the orbit average power than small panel angle

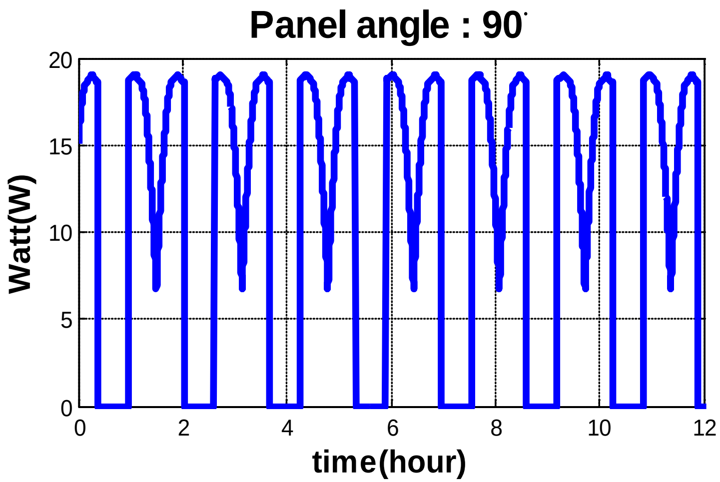


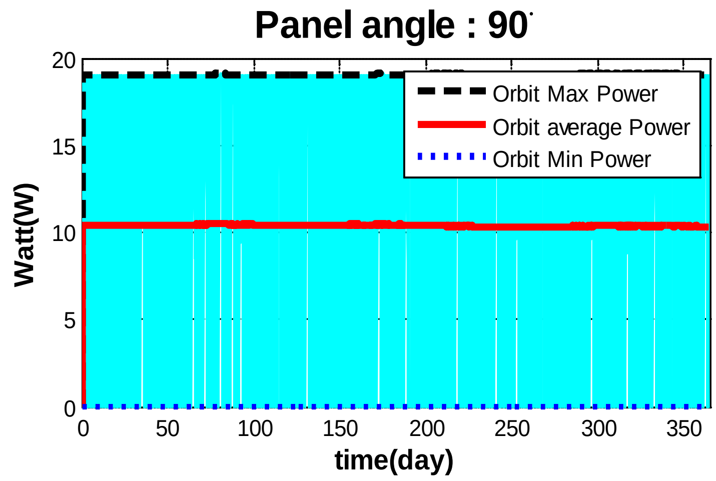
Result Analysis of Sun-Synchronous orbit ('Noon-Midnight' Orbit)

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



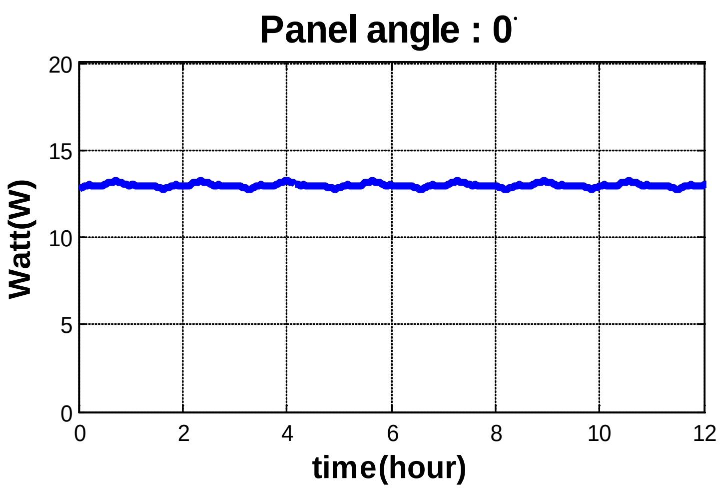


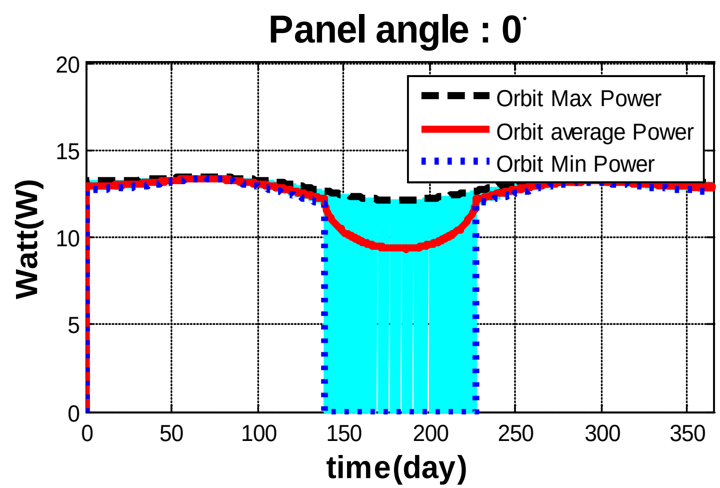


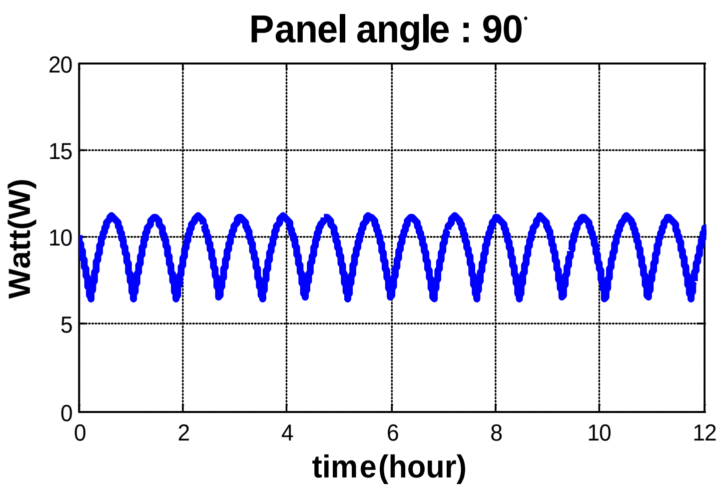


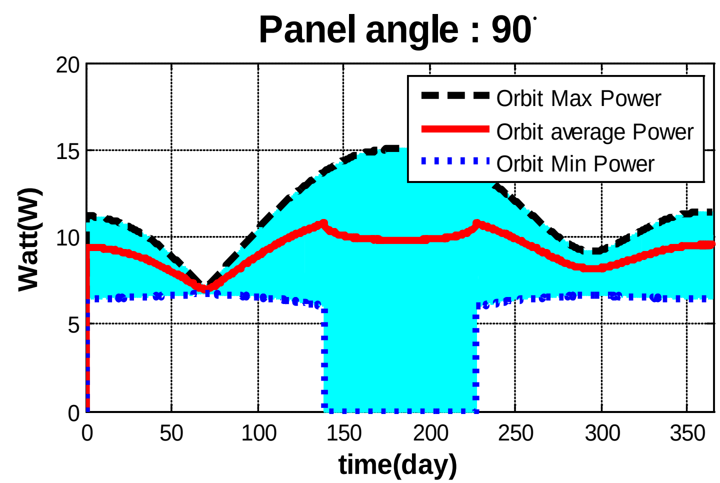
Result Analysis of Sun-Synchronous orbit ('Dawn-Dusk' Orbit)

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









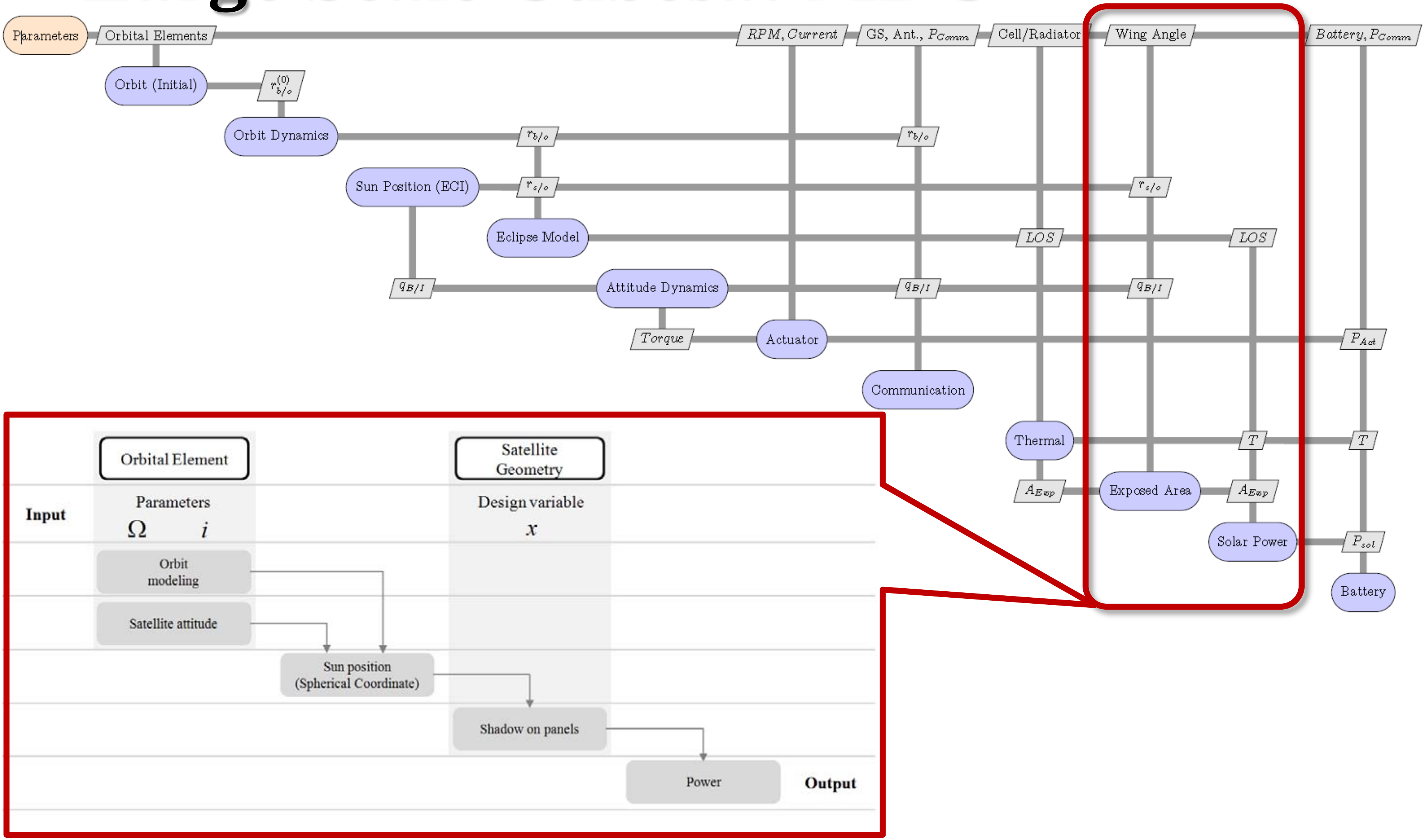
Conclusions

- **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**

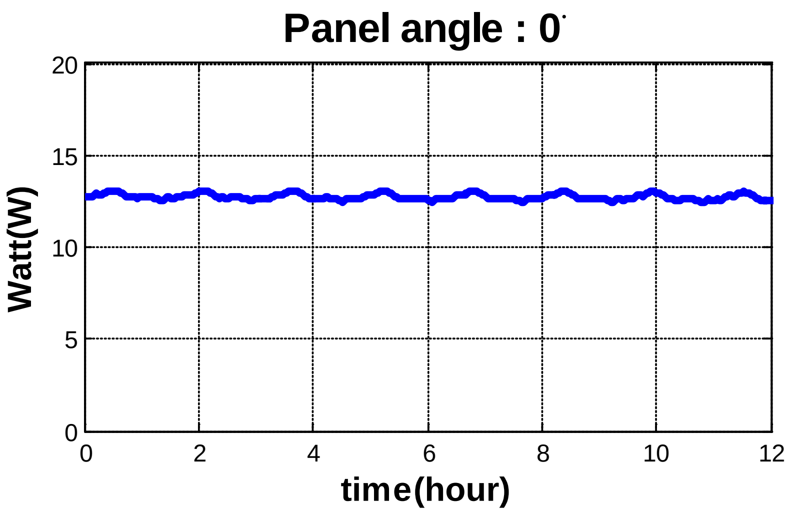
- **Large scale Multidisciplinary Design Optimization(MDO) of Cubesat**
  - **Because the running all possible case simulation is very exhaustive and not practical**
  - **Researching ‘Gradient based optimization’**

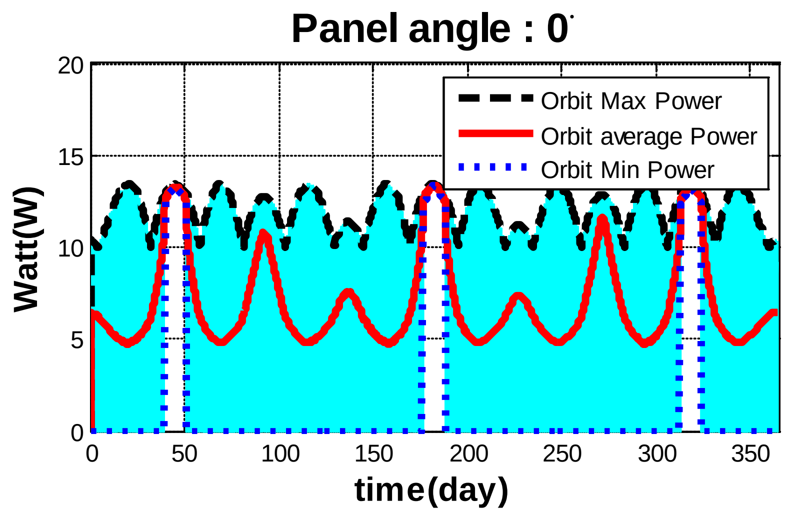
Large Scale Cubesat MDO

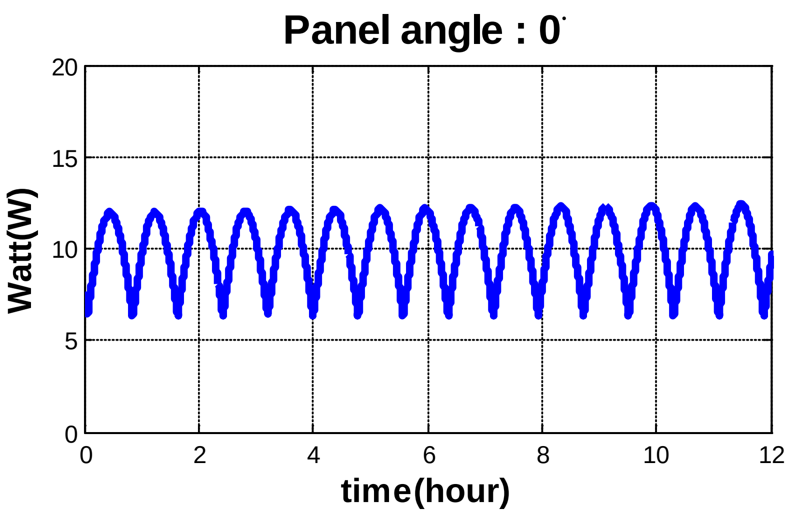


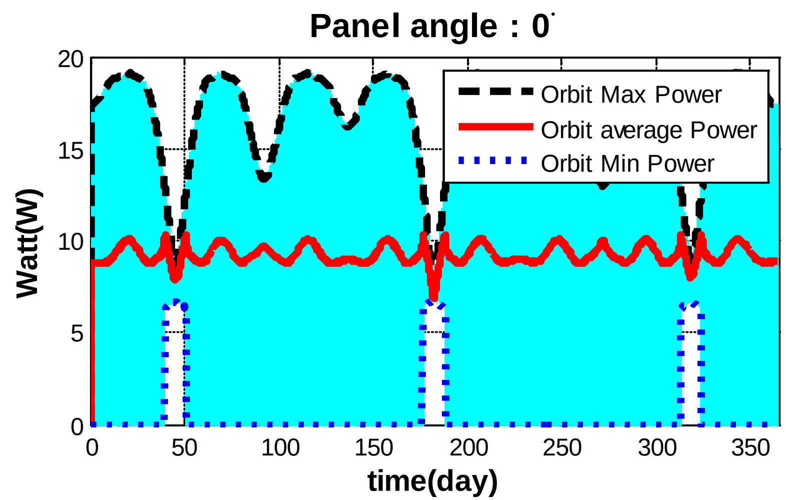
Result Analysis of Non Sun-Synchronous orbit (Inclination : 67°)

- Day = 50



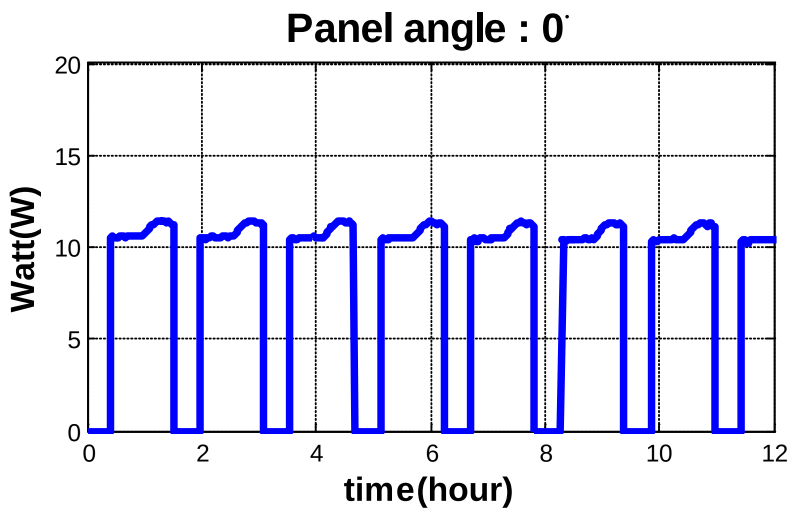


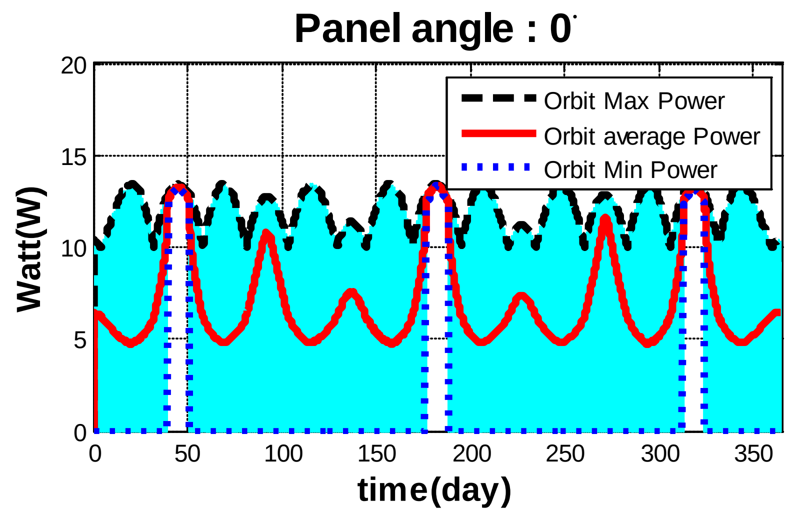


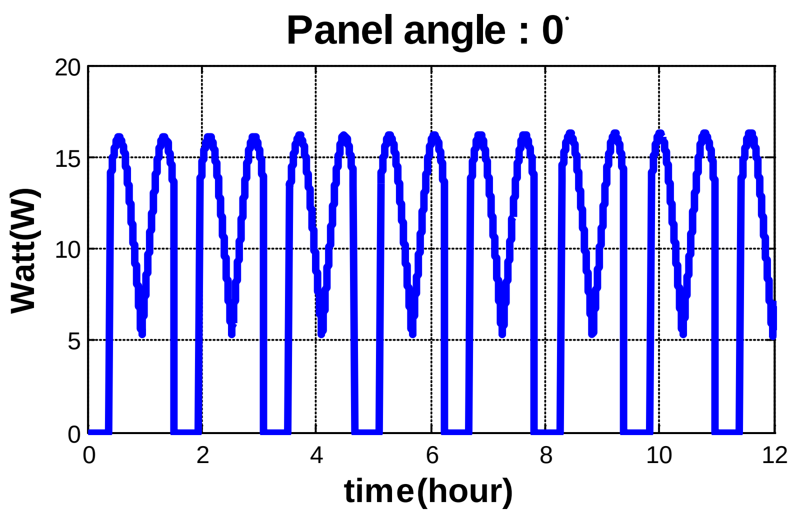


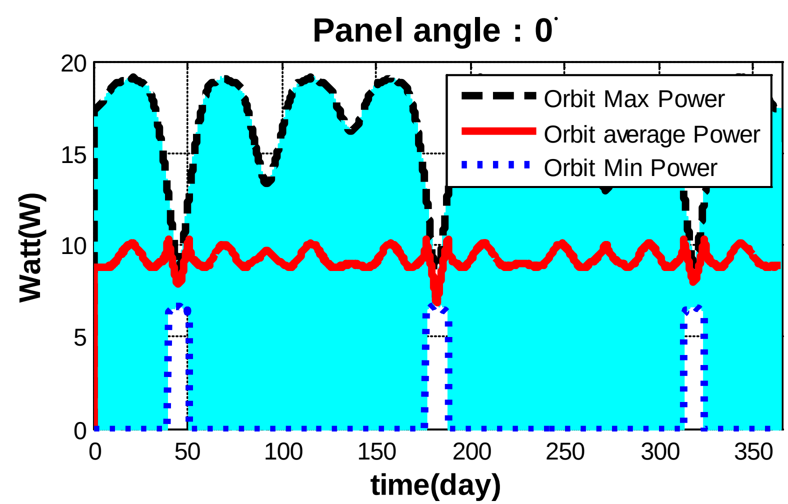
Result Analysis of Non Sun-Synchronous orbit (Inclination : 67°)

- Day = 100



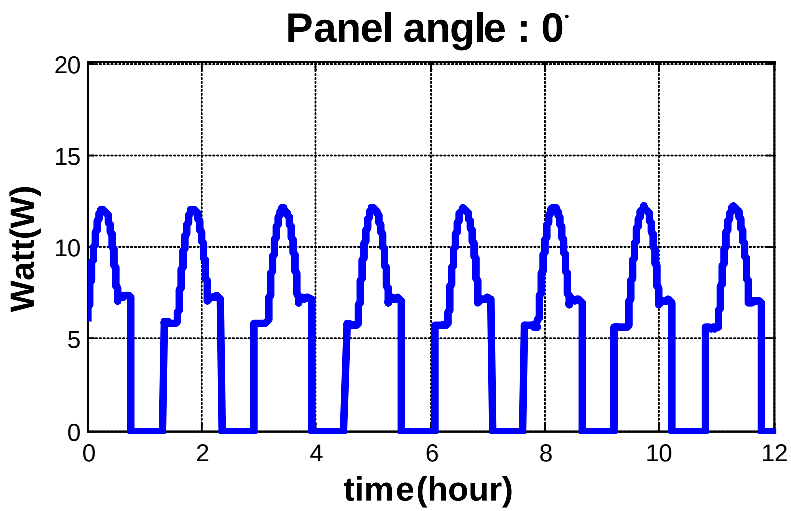


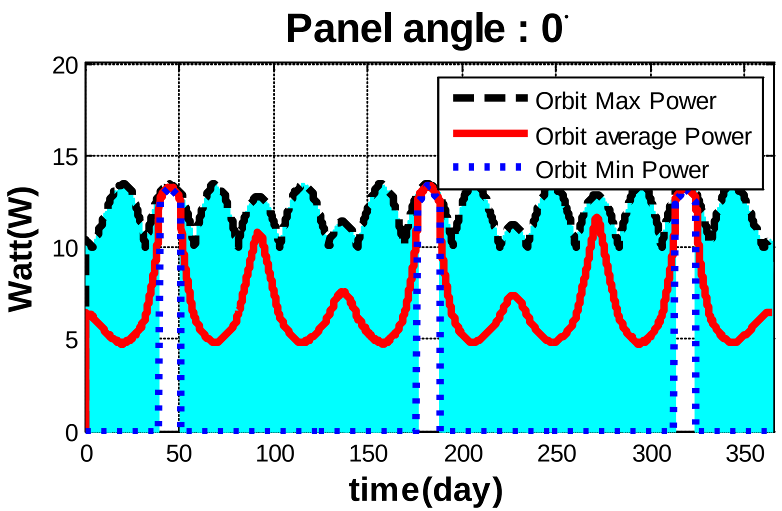


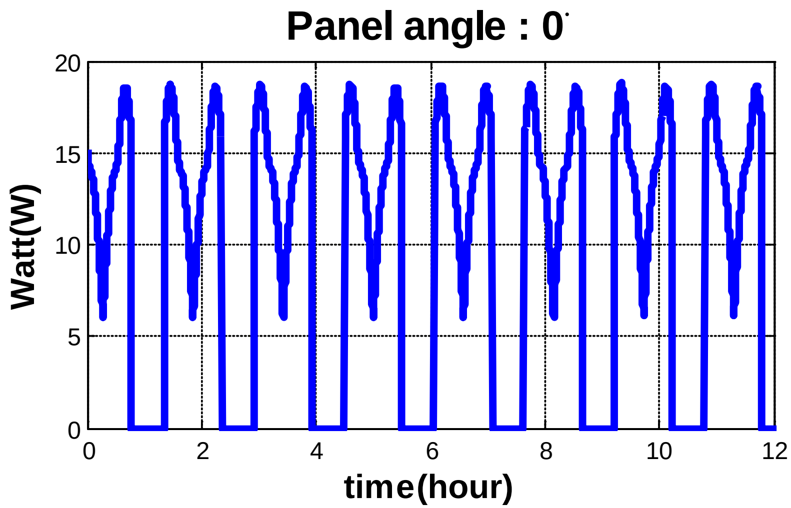


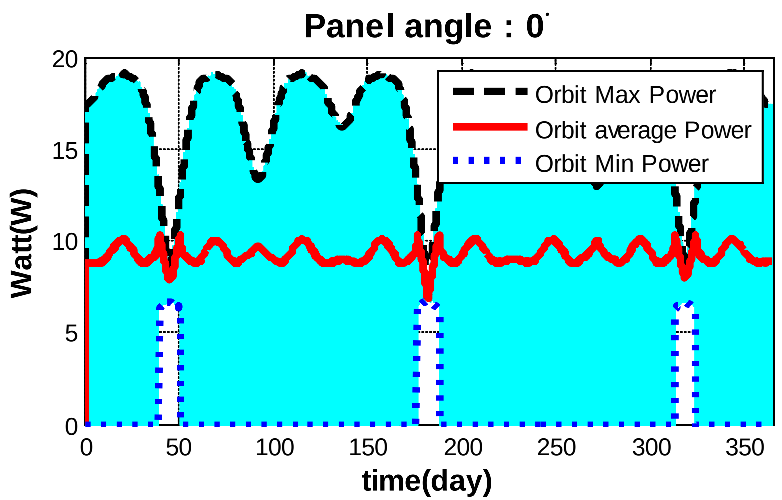
Result Analysis of Non Sun-Synchronous orbit (Inclination : 67°)

- Day = 150



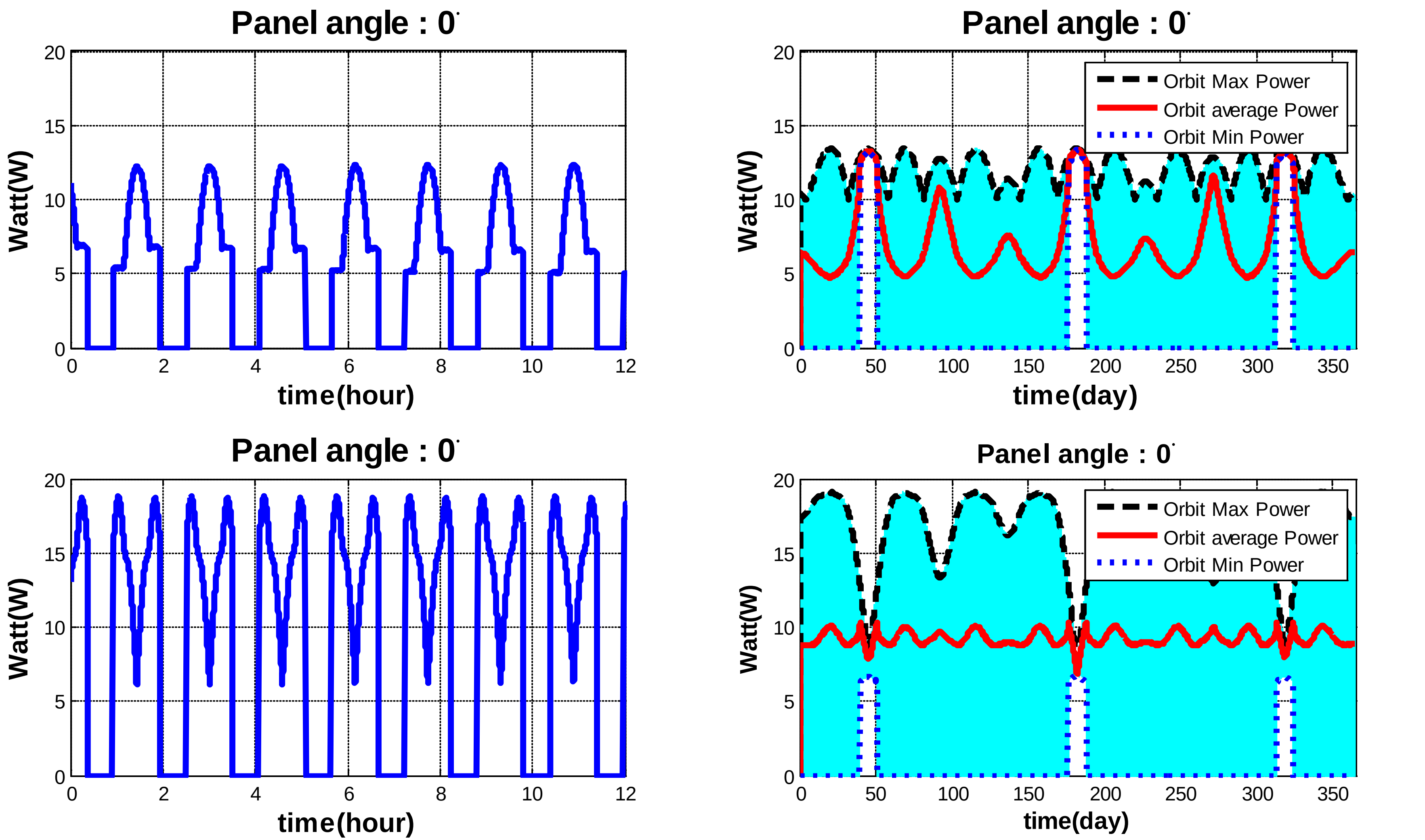






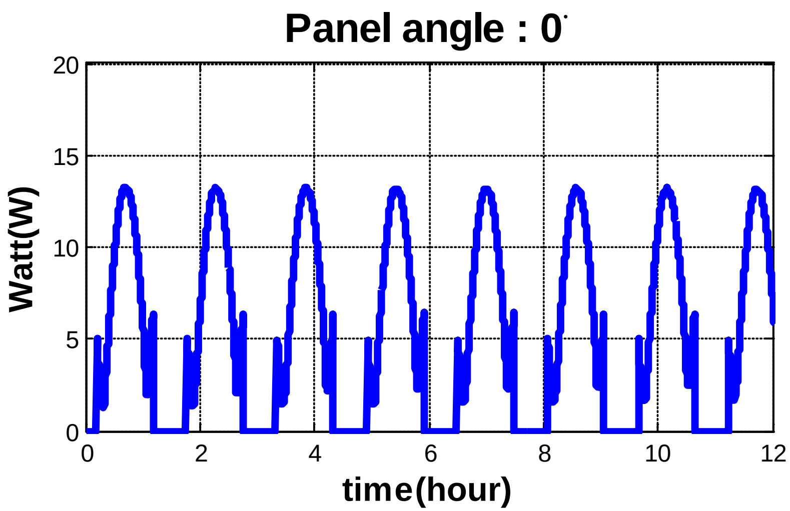
Result Analysis of Non Sun-Synchronous orbit (Inclination : 67°)

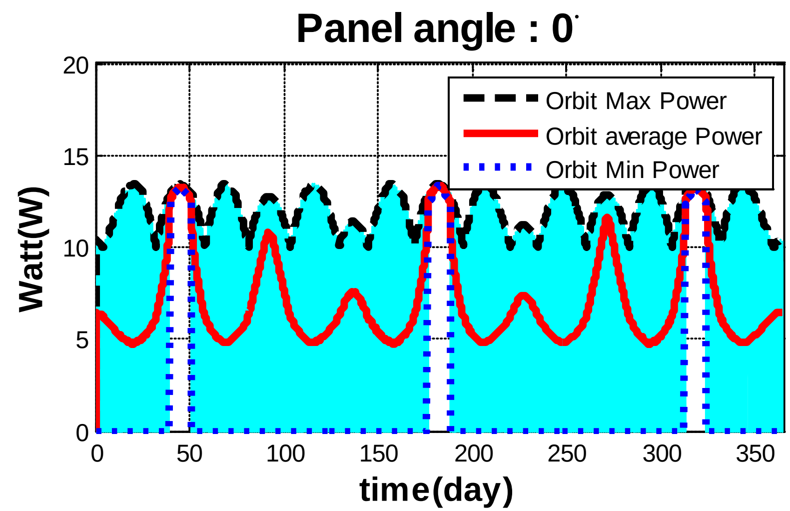
- Day = 200

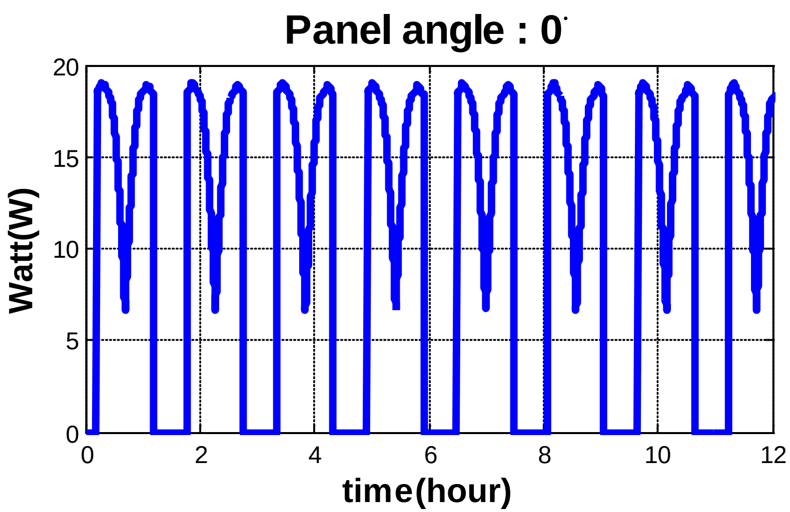


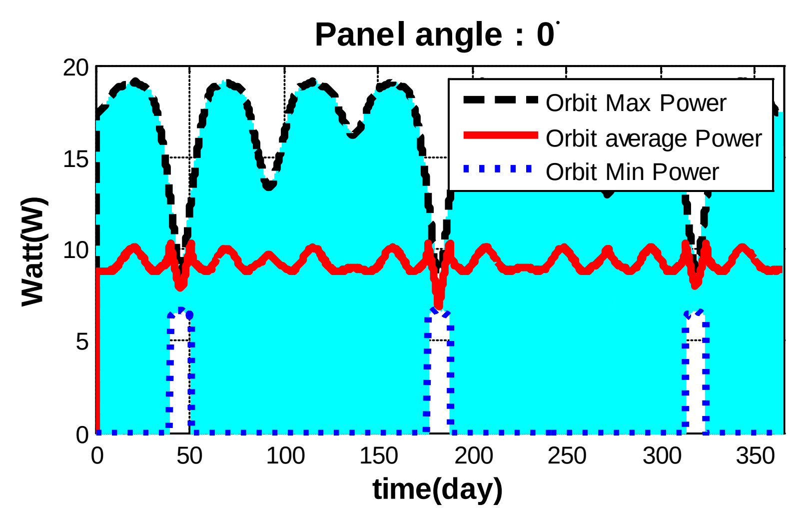
Result Analysis of Non Sun-Synchronous orbit (Inclination : 67°)

- Day = 250



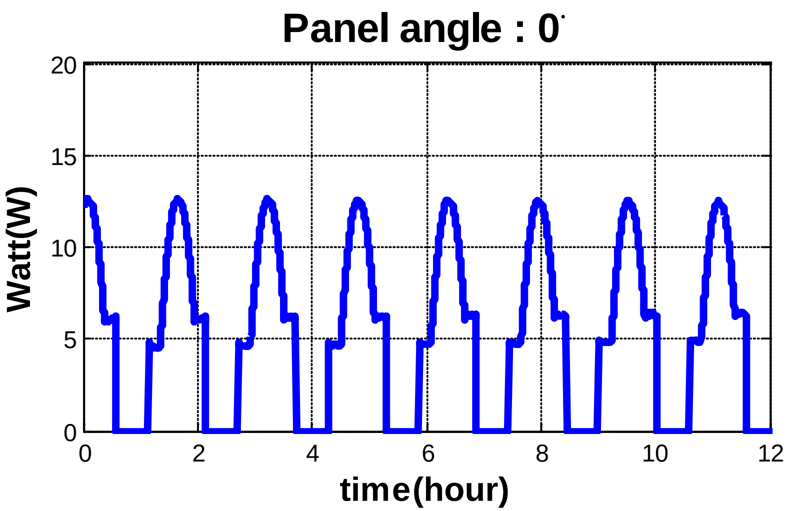


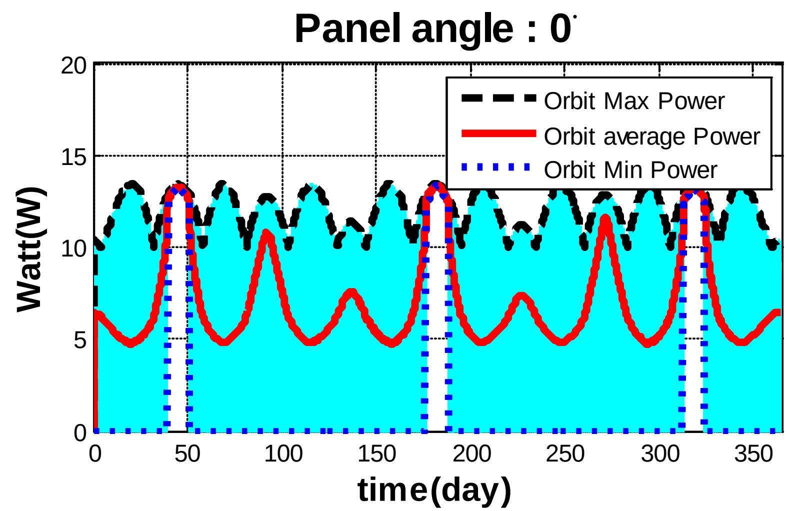


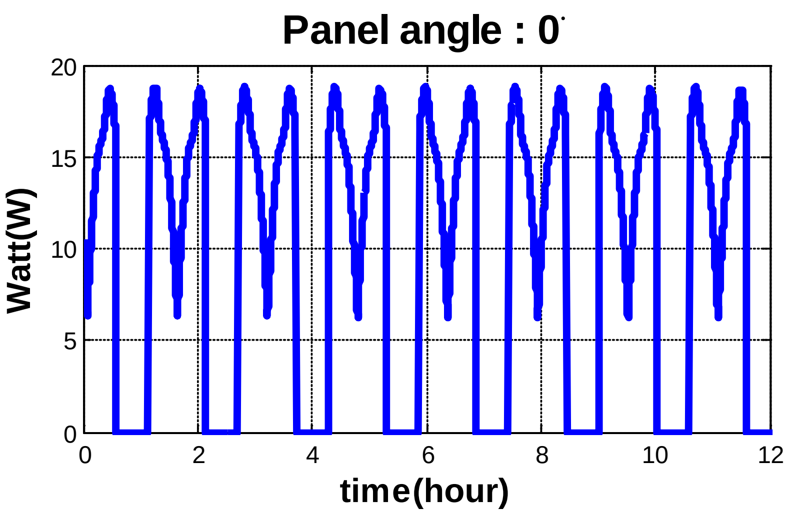


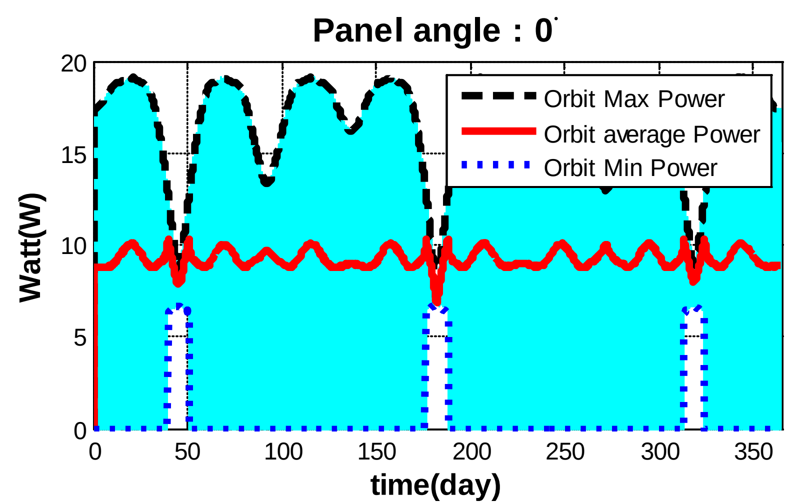
Result Analysis of Non Sun-Synchronous orbit (Inclination : 67°)

- Day = 300



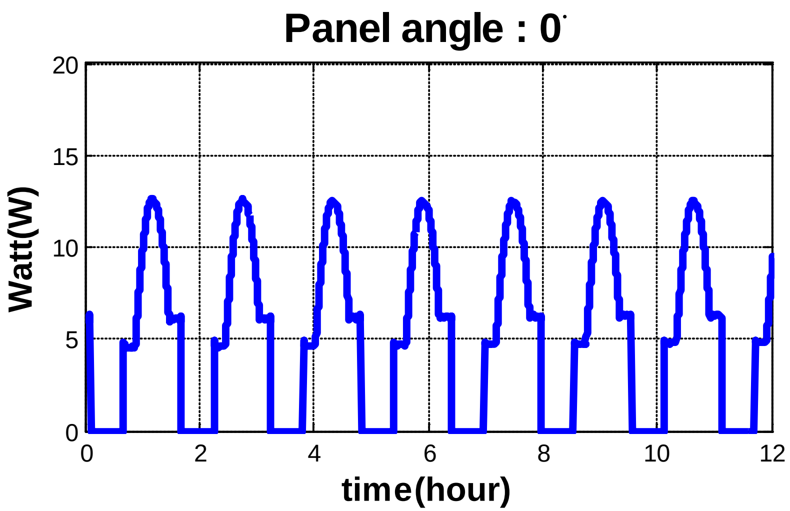


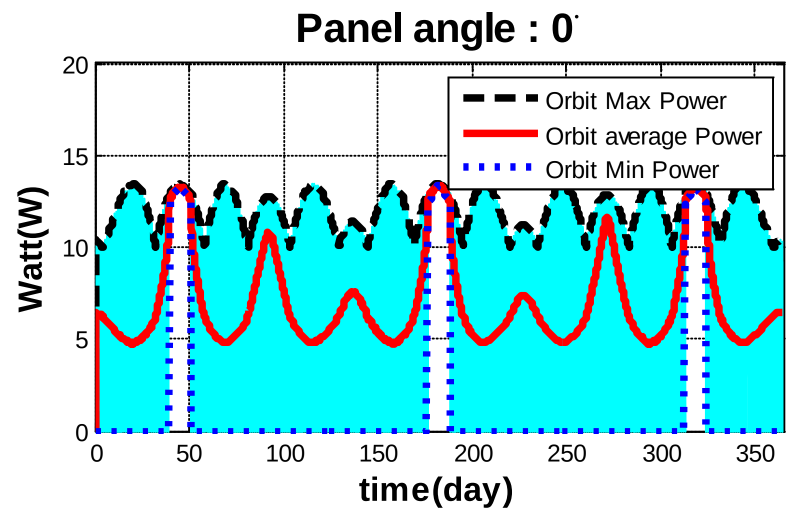


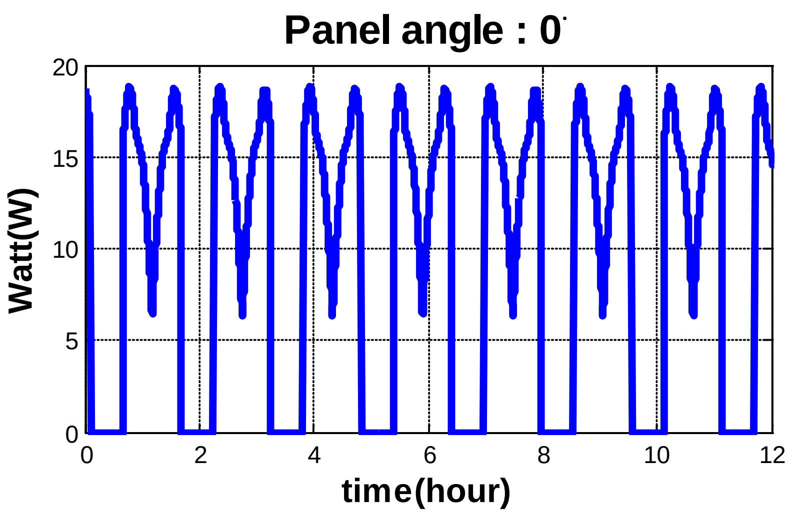


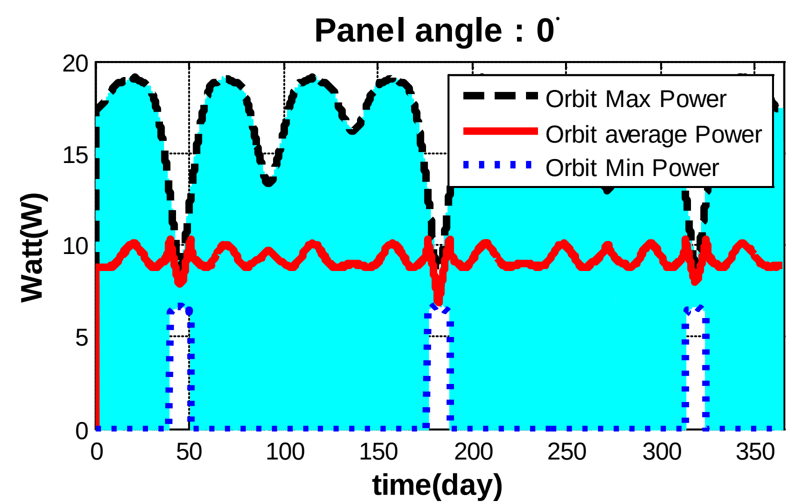
Result Analysis of Non Sun-Synchronous orbit (Inclination : 67°)

- Day = 350





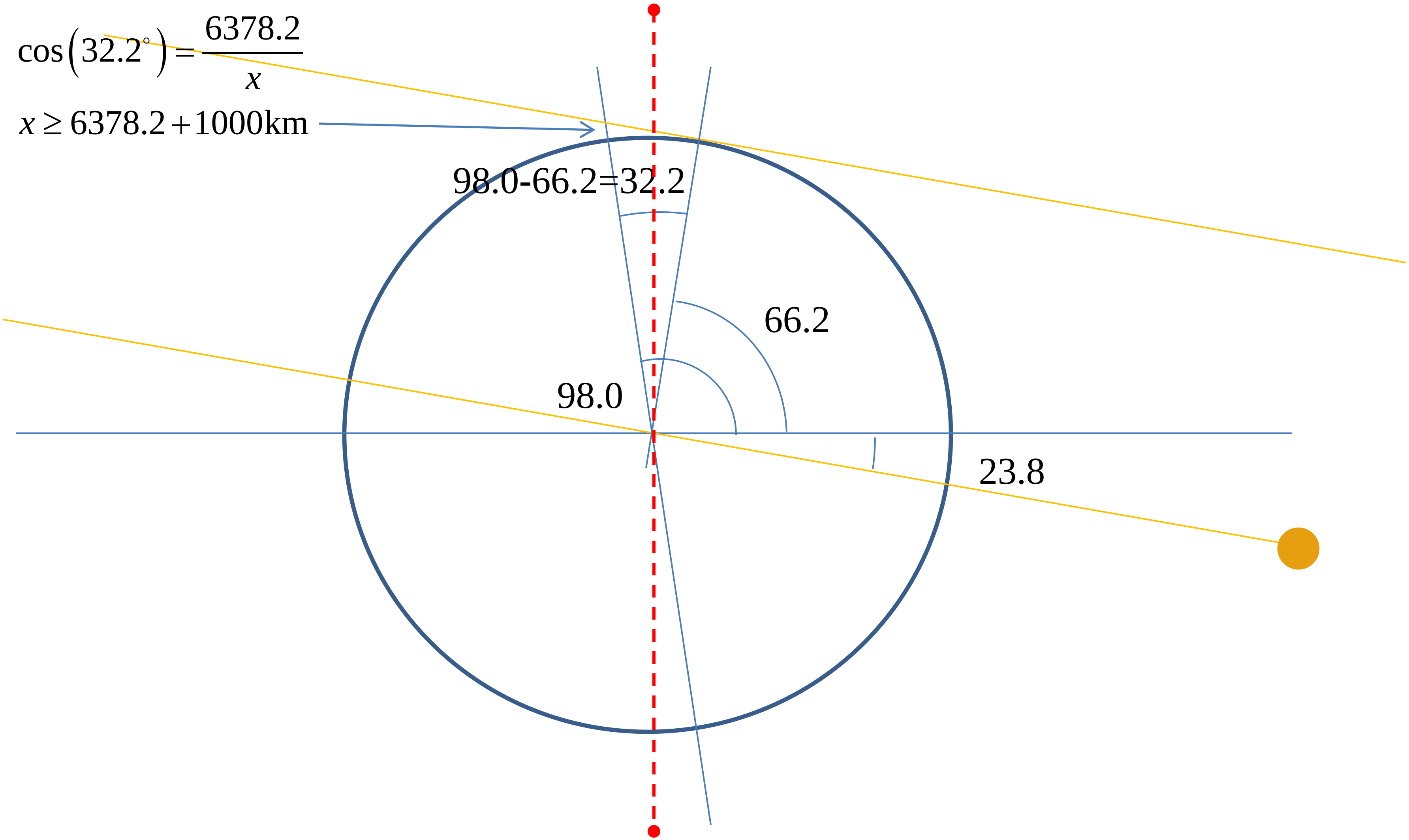




Eclipse of the Dawn-Dusk, in the Low Earth Orbit

$$\cos\left(32.2^{\circ}\right)=\frac{6378.2}{x}$$

$$x \geq 6378.2+1000\text{km}$$



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

- Comparison between different angles