The 1st APSCO & ISSI-BJ Space Science School

# Multidisciplinary Design Optimization for an All-electric GEO Satellite

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# Outline

- Introduction
- AETS MDO problem definition
- Multidisciplinary modeling for AETS
- Surrogate assisted design optimization
- Summary

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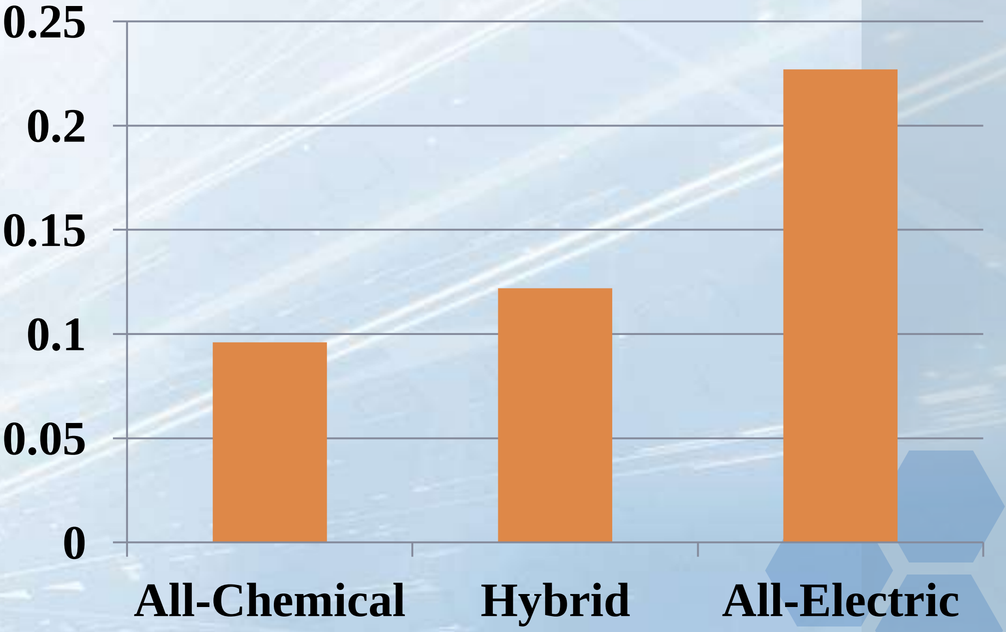
# Introduction

Since the dawn of the space era, the satellites in geosynchronous orbit have gained great interests because of the merits in communications, earth observation, navigation, etc. **State-of-the-art GEO satellites are capable of using electric thrusters to perform all propulsive tasks like orbit-raising and station-keeping**. Compared with conventional GEO satellites using the all-chemical or hybrid propulsion systems, **all-electric GEO satellite can save considerable amount of propellant owing to the superior efficiency of electric propulsion (EP) system**, which results in significant reduction of the launch cost and additional payloads.

**BSS-702SP of Boeing**



**Payload Ratio of different propulsion model**

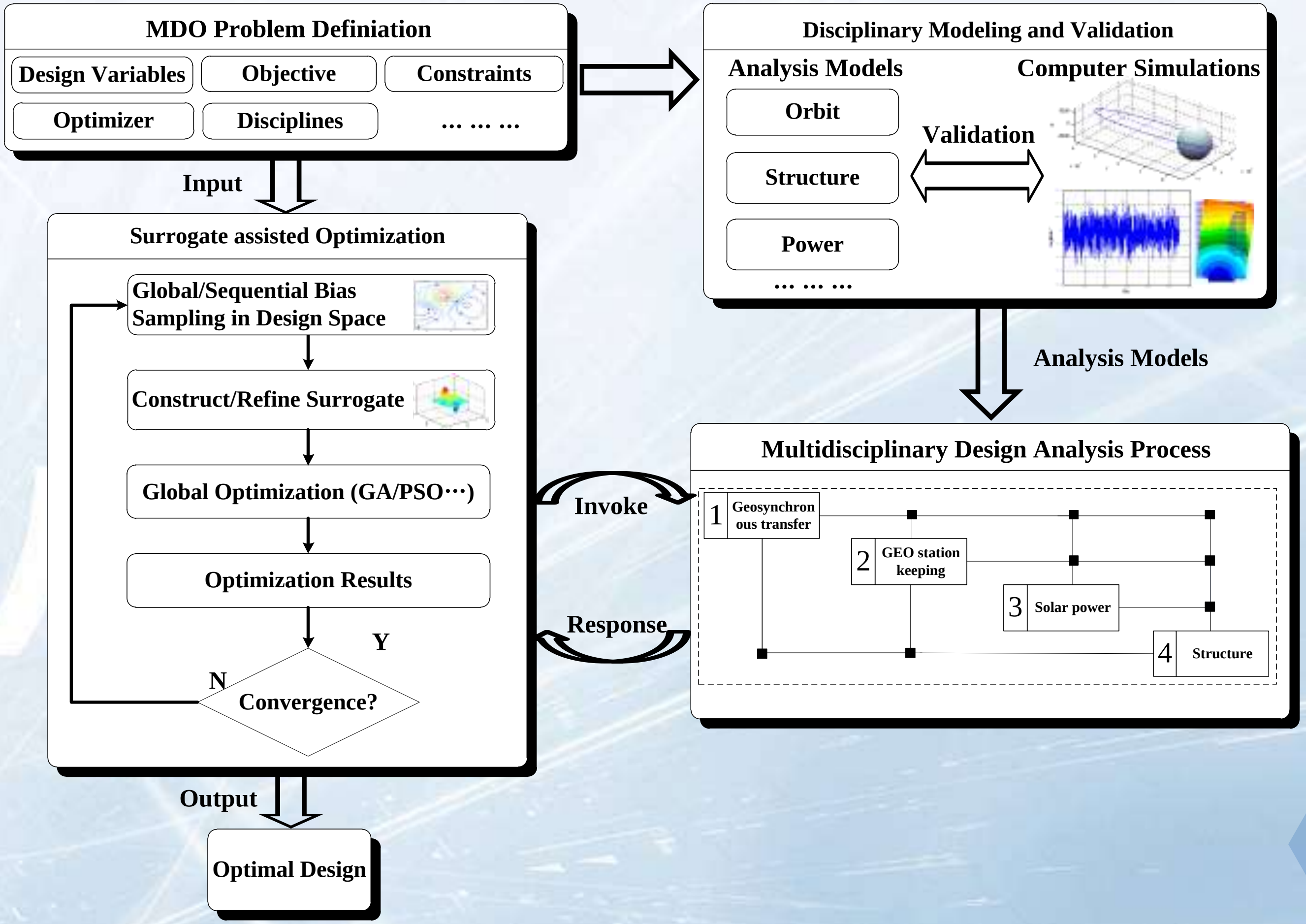
# Introduction

Although all-electric GEO satellites consume much less propellant than the competitive chemical ones, it requires extremely long transfer time due to the low thrust produced by electric thrusters. Not only does this delay the deployment of GEO satellites, but also result in serious radiation damage of devices like solar arrays caused by the prolonged transfer time within the Van Allen belts. It requires that the design of geosynchronous transfer orbit, station-keeping strategy, power, attitude control, propulsion, and structure subsystems, etc. should be considered simultaneously.

Hence, the designers must make tradeoffs among different subsystems (disciplines) of an all-electric satellite. **Multidisciplinary design optimization (MDO)** is therefore preferred to deal with the satellite system design problems. MDO was originally proposed by Sobieski , which was defined as "**a methodology for the design of complex engineering systems and subsystems that coherently exploits the synergy of mutually interacting phenomena**" by NASA's Langley Research Center.

# Introduction

**A surrogate assisted MDO framework** is utilized to handle the all-electric GEO satellite multidisciplinary design optimization problem.



MDO Problem Definiation

Design Variables

Objective

Constraints

Optimizer

Disciplines

… … …

Input

Surrogate assisted Optimization

Global/Sequential Bias Sampling in Design Space

Construct/Refine Surrogate

Global Optimization (GA/PSO⋯)

Optimization Results

Y

N

Convergence?

Output

Optimal Design

Disciplinary Modeling and Validation

Analysis Models

Computer Simulations

Orbit

Structure

Power

… … …

Validation

Analysis Models

Multidisciplinary Design Analysis Process

Invoke

Response

1 Geosynchronous transfer

2 GEO station keeping

3 Solar power

4 Structure

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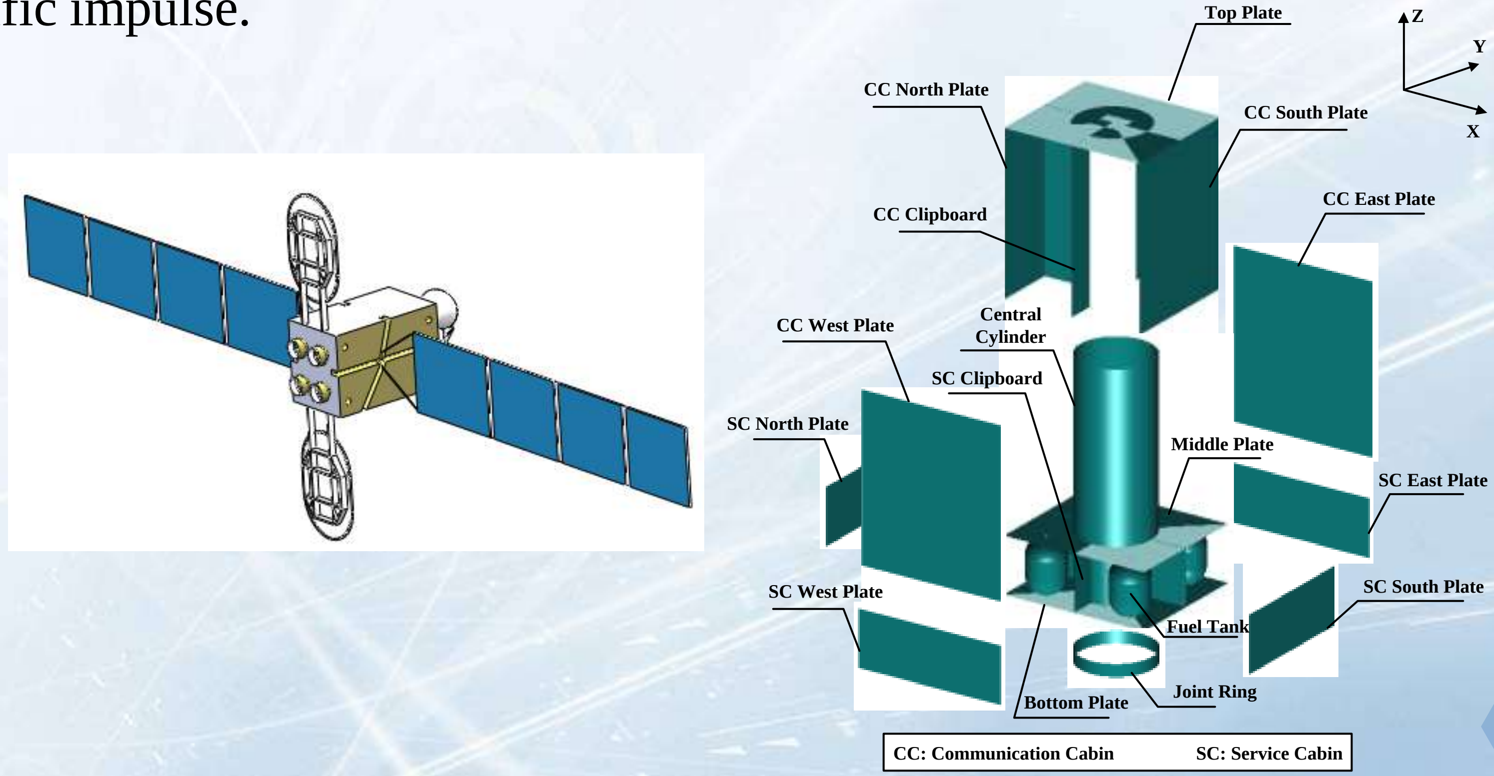
# AETS MDO problem definition

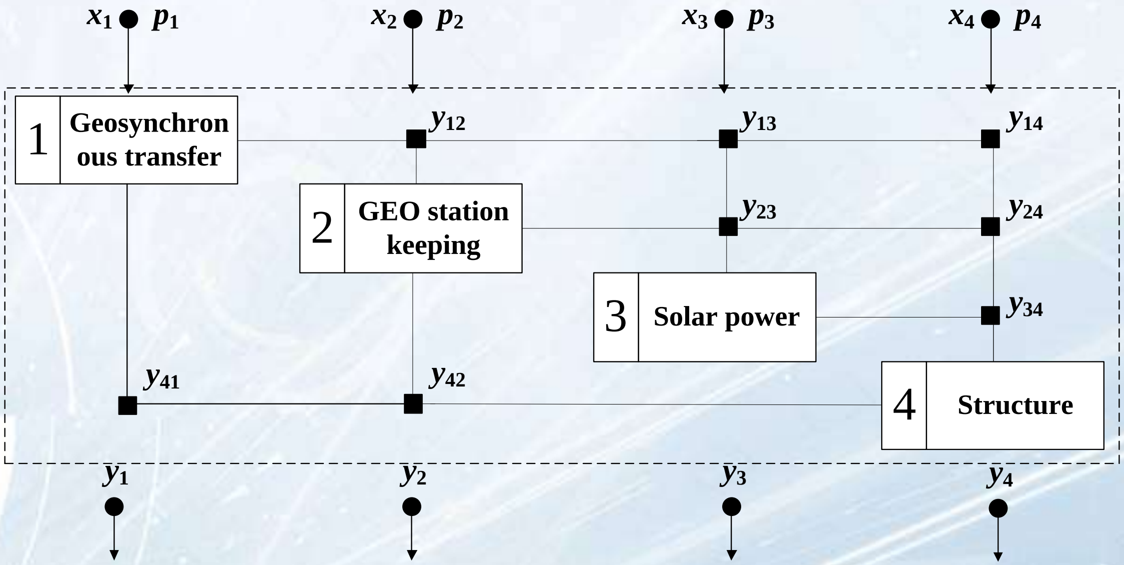
The studied **all-electric telecommunication satellite (AETS)** is a kind of GEO communication satellite. AETS comprises payload module, service module, solar arrays, and payloads. **AETS uses four ion thrusters mounted on the bottom of the satellite to execute geosynchronous transfer and GEO station keeping maneuvers**. The ion thrusters can provide a maximum thrust of 200mN with 4.5kW power and 4000s specific impulse.



**Studied all-electric telecommunication satellite**

# AETS MDO problem definition

In view of the typical characteristics of all-electric GEO satellite, we mainly choose the **geosynchronous transfer**, **GEO station-keeping**, **solar power**, and **structure** as the modeled disciplines for AETS MDO problem. The coupling relationship for the MDO problem is organized in **design structure matrix (DSM).**



$x_1$ $p_1$ $x_2$ $p_2$ $x_3$ $p_3$ $x_4$ $p_4$

1 Geosynchronous transfer

2 GEO station keeping

3 Solar power

4 Structure

$y_{12}$ $y_{13}$ $y_{14}$ $y_{23}$ $y_{24}$ $y_{34}$ $y_{41}$ $y_{42}$

$y_1$ $y_2$ $y_3$ $y_4$

**Design Structure Matrix of the MDO problem**

$$\min \quad M_{\text{satellite}} = f(\boldsymbol{X}), \boldsymbol{X} = [\boldsymbol{x}_1, \boldsymbol{x}_2, \boldsymbol{x}_3, \boldsymbol{x}_4]^T$$

$$s.t \quad \begin{cases} D_i(\boldsymbol{x}_i, \boldsymbol{y}_i, \boldsymbol{y}_{ij}) = 0, i = 1,2,3,4 \\ C_i(\boldsymbol{x}_i, \boldsymbol{y}_i, \boldsymbol{y}_{ij}) \le 0, i = 1,2,3,4 \end{cases}$$

# AETS MDO problem definition

- **Design Variables of the MDO problem**

| Design variable | Symbol | Unit | Range |
|---|---|---|---|
| Thrust angle in the first GTO stage | $\alpha$ | ° | [0,60°] |
| The $T$ position of thruster | $d_T$ | mm | [500,1180] |
| The $N$ position of thruster | $d_N$ | mm | [800,1050] |
| Solar array area | $A_{sa}$ | m$^2$ | [100,120] |
| Core thickness of service cabin SN\EW plates | SH | mm | [17,25] |
| Core thickness of communication cabin SN\EW plates | CH | mm | [17,25] |
| Core thickness of central cylinder | TBH | mm | [17,25] |
| Ply thickness of service cabin SN\EW plates | SP | mm | [2.8e-4,5.2e-4] |
| Ply thickness of communication cabin SN\EW plates | CP | mm | [2.8e-4,5.2e-4] |
| Ply thickness of bearing cylinder | TBP | mm | [7e-5,1.3e-4] |

# AETS MDO problem definition

- **Constraints of the MDO problem**

| Constraint | Symbol | Unit | Range |
|---|---|---|---|
| Total orbit transfer time | $t_f$ | Day | $\leq 180$ |
| EWSK accuracy | $\lambda_{\max}$ | ° | $\leq 0.05$ |
| NSSK accuracy | $i_{\max}$ | ° | $\leq 0.05$ |
| Beginning-of-life power | $P_{BOL}$ | kW | $\geq 22.90$ |
| Ending-of-life power | $P_{EOL}$ | kW | $\geq 16.30$ |
| First order rotational modal round X | $f_X$ | Hz | $\geq 12$ |
| First order rotational modal round Y | $f_Y$ | Hz | $\geq 12$ |
| First order translational modal round Z | $f_Z$ | Hz | $\geq 25$ |

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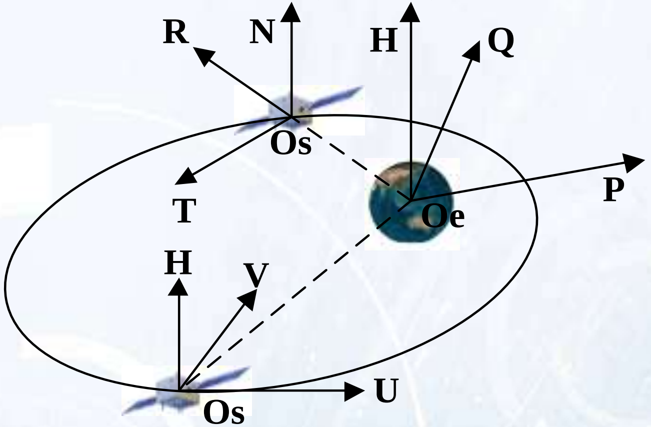
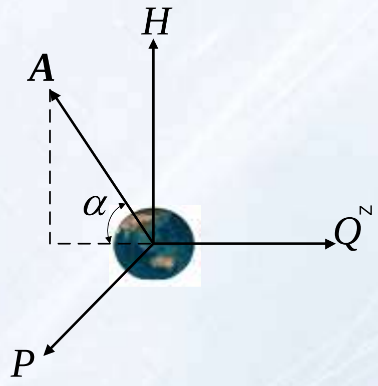
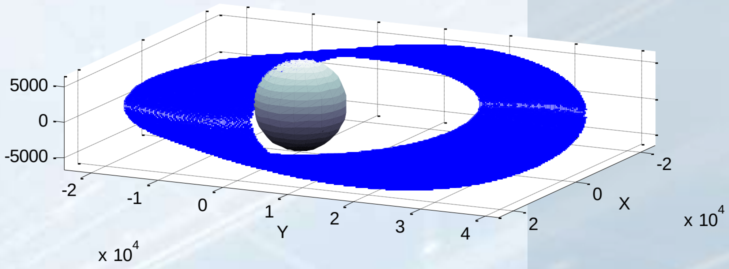
# Multidisciplinary modeling for AETS

## ➢ Geosynchronous transfer discipline modeling

A two-stage electric propulsion transfer is utilized to determine the geosynchronous transfer orbit (GTO) to accomplish low continuous thrust GEO insertion of the satellite.

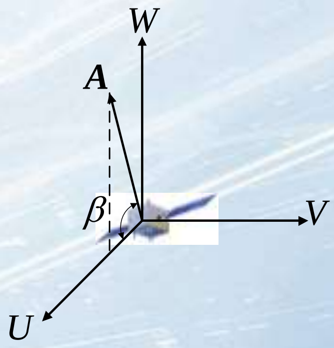


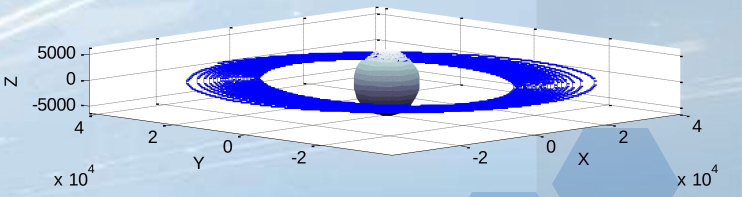




**In the first stage, the eccentricity is reduced to 0.**

$$
\begin{cases}
\dfrac{\mathrm{d}a}{\mathrm{d}t} = \dfrac{2}{n\sqrt{1-e^2}}(F_R e \sin f + F_T(1 + e\cos f)) \\
\dfrac{\mathrm{d}e}{\mathrm{d}t} = \dfrac{\sqrt{1-e^2}}{na}(F_R \sin f + F_T(\cos f + \cos E)) \\
\dfrac{\mathrm{d}i}{\mathrm{d}t} = \dfrac{r\cos u}{na^2\sqrt{1-e^2}} F_N \\
\dfrac{\mathrm{d}\Omega}{\mathrm{d}t} = \dfrac{r\sin u}{na^2\sqrt{1-e^2}\sin i} F_N \\
\dfrac{\mathrm{d}\omega}{\mathrm{d}t} = \dfrac{\sqrt{1-e^2}}{nae}(-F_R\cos f + F_T(1+\dfrac{r}{p})\sin f) - \cos i\dfrac{\mathrm{d}\Omega}{\mathrm{d}t} \\
\dfrac{\mathrm{d}M}{\mathrm{d}t} = n - \dfrac{1-e^2}{nae}(-F_R(\cos f - 2e\dfrac{r}{p}) + F_T(1+\dfrac{r}{p})\sin f)
\end{cases}
$$



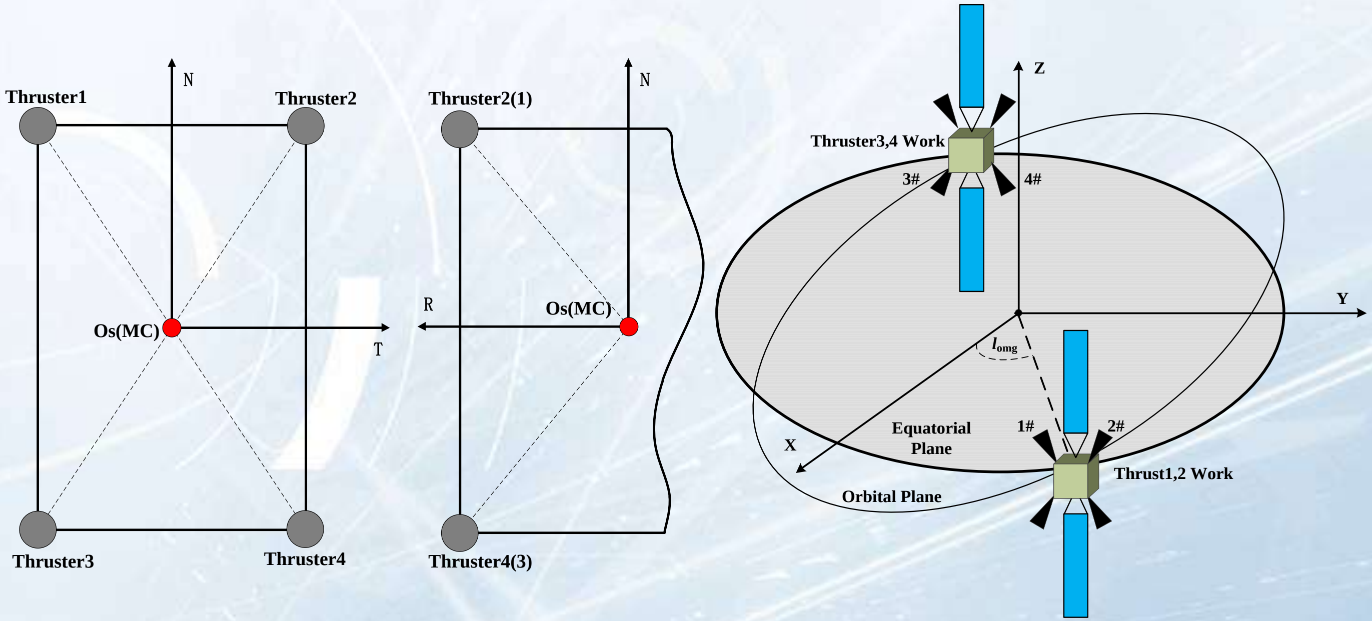


**In the second stage, the semi-major axis is increased to 42166km and the inclination is reduced to 0° .**

# Multidisciplinary modeling for AETS

## ➢ GEO station-keeping discipline modeling

The GEO position-keeping discipline models the **north/south station keeping (NSSK)** and **east/west station keeping (EWSK)** maneuvers implemented by EP system to determine the thruster installation configuration. A completed EP position keeping period lasts for two weeks with seven short periods of two days.



$$
\begin{cases}
\Delta D = -\dfrac{3}{a_s}\Delta V_T \\
\Delta \lambda = -2\dfrac{\Delta V_R}{V_s} \\
\Delta e_x = \dfrac{\Delta V_R}{V_s}\sin l + 2\dfrac{\Delta V_T}{V_s}\cos l \\
\Delta e_y = -\dfrac{\Delta V_R}{V_s}\cos l + 2\dfrac{\Delta V_T}{V_s}\sin l \\
\Delta i_x = \dfrac{\Delta V_N}{V_s}\cos l \\
\Delta i_y = \dfrac{\Delta V_N}{V_s}\sin l
\end{cases}
$$

**Illustration of thrusters on the bottom and GEO position keeping strategy**

# Multidisciplinary modeling for AETS

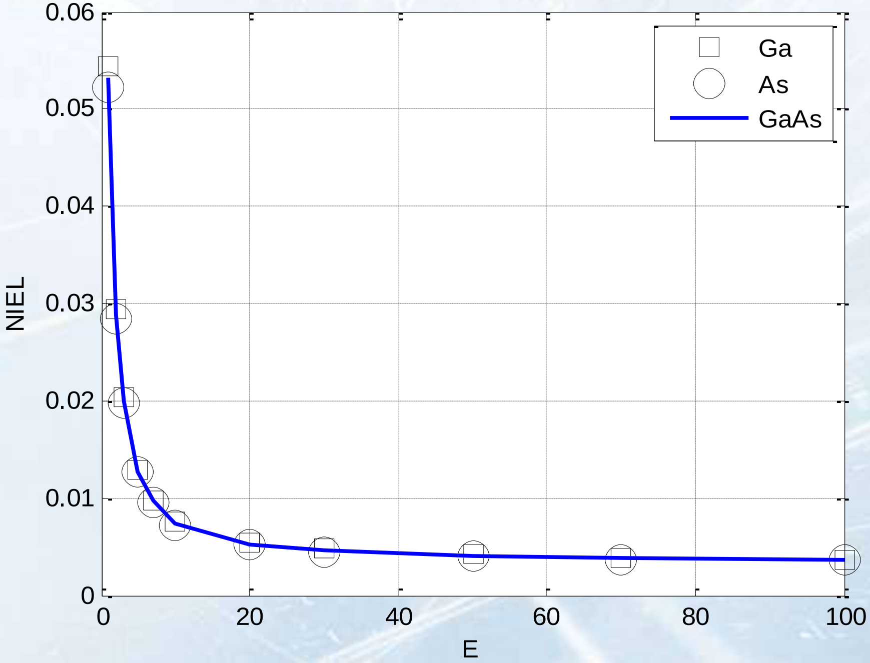
## ➢ Solar power discipline modeling

The solar power discipline computes the area of solar arrays to provide sufficient available power.

$$P_0 = (1-\boxed{p_r})S_0 X X_s X_e X_0 A_{sa} \eta F_c (\beta_p \Delta T + 1)\cos\chi$$

**Power Degradation Coefficient Calculation**

The **NASA AP8 Approximation Model** is utilized to compute the omnidirectional radiation flux of protons, the non-ionizing energy loss (NIEL) of solar arrays (Gallium Arsenide) is computed by the interpolation result of experimental data.



$$\psi(L,\lambda,E) = a(L,E)e^{-b(L,E)l^2}$$

$$L = \frac{r}{R\cos^2 l}$$

$$a(L,E) = a_0 e^{a_1 E + a_2 (a_3 + L)^2}$$

$$b(L,E) = b_0 + b_1 E + b_2 L + b_3 EL + b_4 EL + b_4 L^2 + b_5 L^3$$

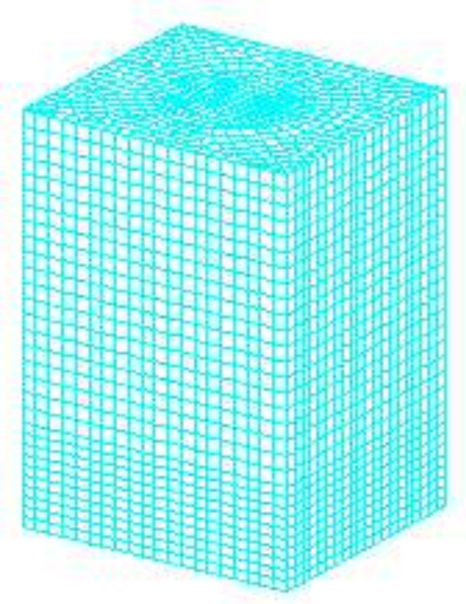
$$D_d(E) = \phi(E) NIEL(E)$$

$$p_r = K\log(1+\frac{D_d}{D_x})$$

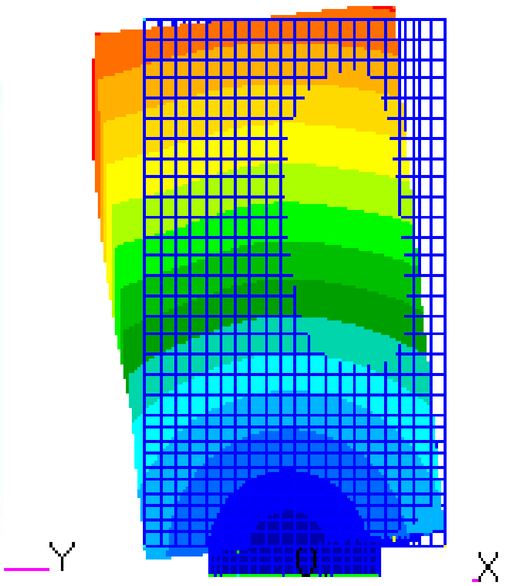
# Multidisciplinary modeling for AETS

## ➢ Structure discipline modeling

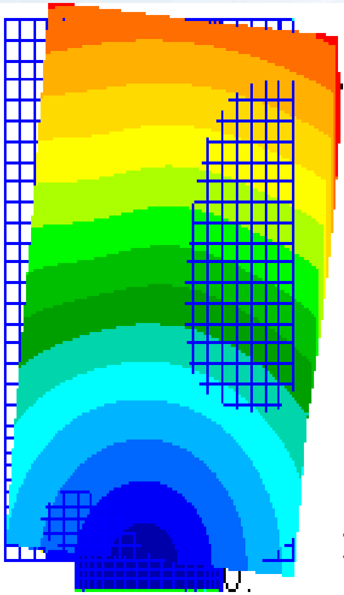
The structure discipline establishes the structural finite element (FE) model of the satellite based on the given configuration to obtain the mass properties and natural frequencies. The structural FE model of the all-electric GEO satellite is established by Patran/Nastran including 6235 elements and 5991 nodes.



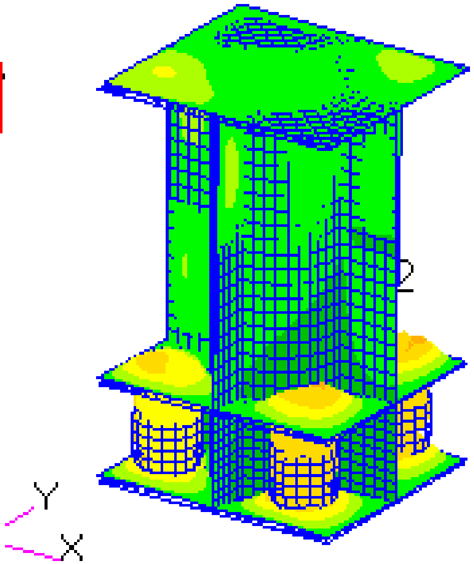
**Finite element model of the Structure**



**1st order rotational modals of X axis**



**1st order rotational modals of Y axis**



**1st order translational modals of Z axis**

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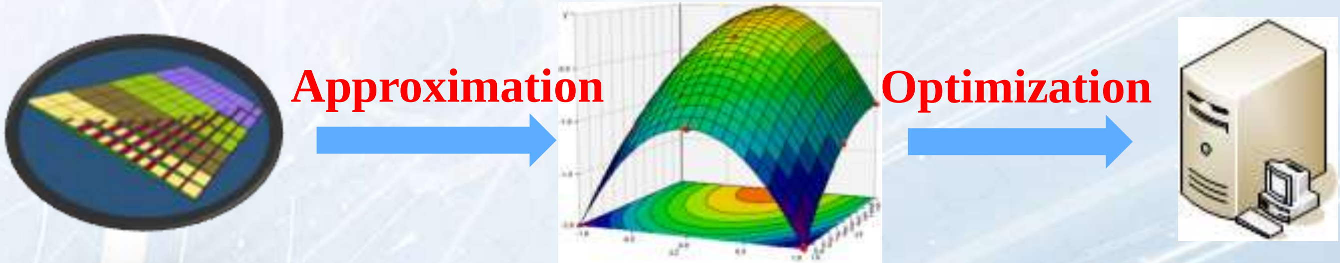
# Surrogate assisted design optimization

## ➢ Review of ARSM-ISES

To reduce the computational cost in solving MDO problems with expensive functions, **surrogate-based analysis and optimization (SBAO) technologies** have been widely employed. In SBAO, a surrogate model is constructed to represent the true computationally expensive analysis model or multidisciplinary design analysis (MDA) process for simulation-based optimization.



**Approximation**

**Optimization**

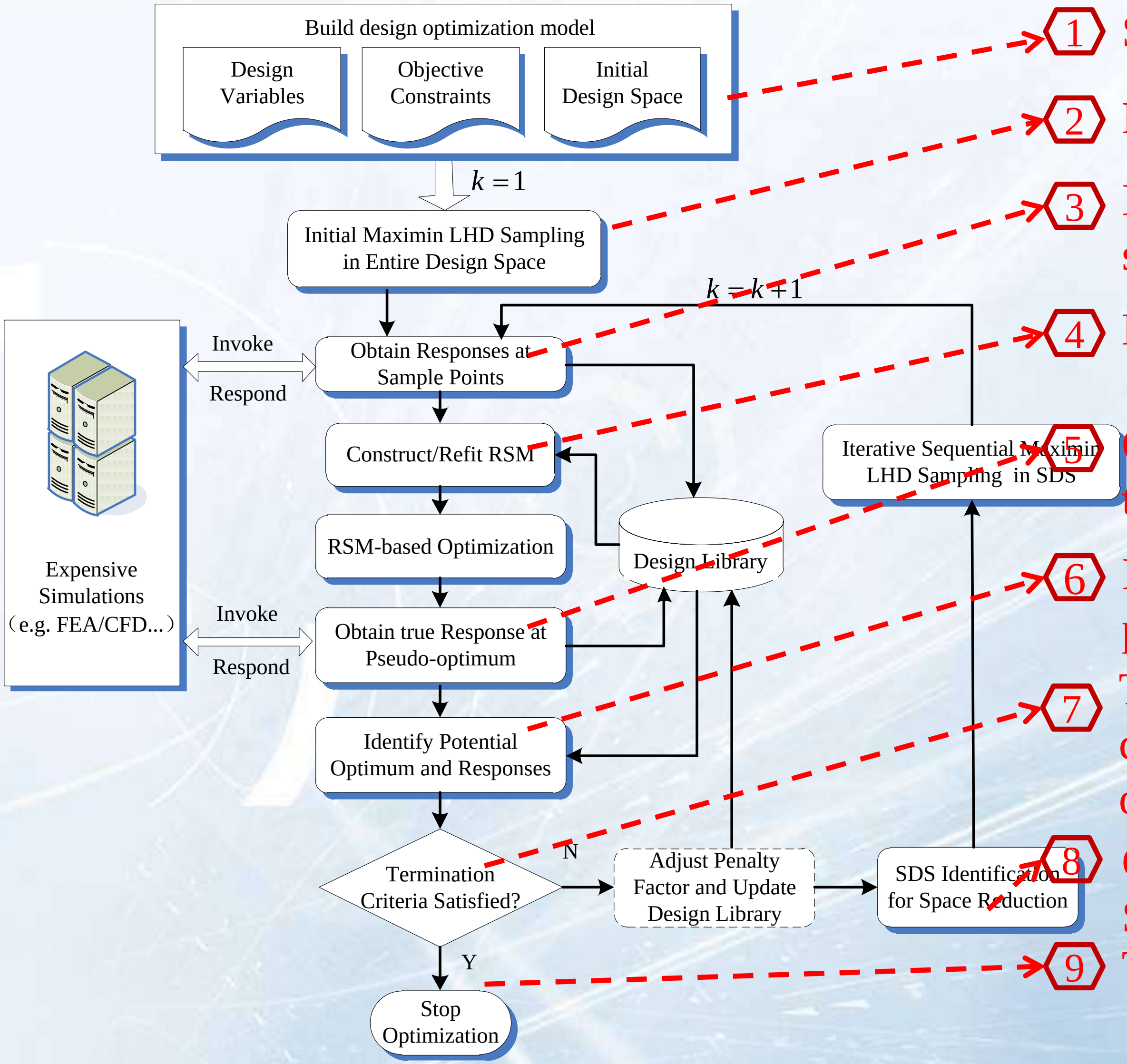
FEM

Surrogate Model

NLP Optimizer

The **adaptive response surface method with intelligent space exploration strategy (ARSM-ISES)** is used to solve the optimization problem.

# Surrogate assisted design optimization

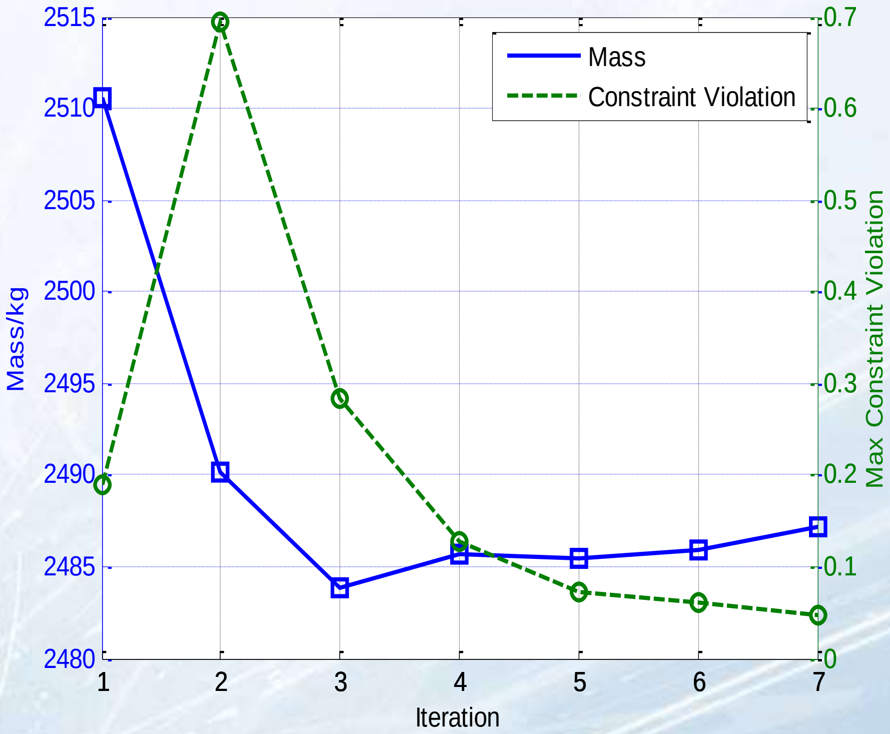


**Flowchart of ARSM-ISES**

1. Set initial conditions
2. LHD sampling
3. Invoke analysis model at the samples
4. Build RSM using current samples
5. Obtain the potential optimum of the iterative metamodel using GA
6. Invoke analysis model at the potential optimum
7. The termination criterion is checked, if satisfied, turn to step 9, otherwise go to step 8
8. Generate new samples using SDS method
9. The process terminates

# Surrogate assisted design optimization

## ➢ Optimization Results



**History curves of objective and maximum constraint violation**

The optimization yields **66.1kg** decrease in total mass, i.e., about **5.4%** of the satellite components being optimized.

# Surrogate assisted design optimization

| Design variable | Symbol | Unit | Range | Initial design | Optimal design |
|---|---|---|---|---|---|
| Thrust angle in the first GTO stage | $\alpha$ | ° | [0,60°] | 0 | 29.79 |
| The *T* position of thruster | $d_T$ | mm | [500,1180] | 1180 | 503.28 |
| The *N* position of thruster | $d_N$ | mm | [800,1050] | 1050 | 962.40 |
| Solar array area | $A_{sa}$ | m$^2$ | [100,120] | 110 | 117.49 |
| Core thickness of service cabin SN\EW plates | SH | mm | [17,25] | 20 | 17.6 |
| Core thickness of communication cabin SN\EW plates | CH | mm | [17,25] | 20 | 17.1 |
| Core thickness of central cylinder | TBH | mm | [17,25] | 20 | 22.4 |
| Ply thickness of service cabin SN\EW plates | SP | mm | [2.8e-4,5.2e-4] | 4e-4 | 3.8e-4 |
| Ply thickness of communication cabin SN\EW plates | CP | mm | [2.8e-4,5.2e-4] | 4e-4 | 3.3e-4 |
| Ply thickness of bearing cylinder | TBP | mm | [7e-5,1.3e-4] | 1e-4 | 7.8e-5 |

# Surrogate assisted design optimization

| Constraint | Symbol | Unit | Range | Initial design | Optimal design |
|---|---|---|---|---|---|
| Total orbit transfer time | $t_f$ | Day | ≤180 | 166.11 | 130.10 |
| EWSK accuracy | $\lambda_{\text{max}}$ | ° | ≤0.05 | 0.035 | 0.027 |
| NSSK accuracy | $i_{\text{max}}$ | ° | ≤0.05 | 0.036 | 0.036 |
| Beginning-of-life power | $P_{BOL}$ | kW | ≥22.90 | 21.41 | 22.90 |
| Ending-of-life power | $P_{EOL}$ | kW | ≥16.30 | 19.86 | 21.20 |
| First order rotational modal round X | $f_X$ | Hz | ≥12 | 13.48 | 12.25 |
| First order rotational modal round Y | $f_Y$ | Hz | ≥12 | 13.39 | 12.16 |
| First order translational modal round Z | $f_Z$ | Hz | ≥25 | 25.55 | 26.17 |

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# Summary

- A surrogate assisted MDO framework consisting of MDO problem definition, disciplinary modeling, and surrogate assisted optimization, is introduced to efficiently implement the state-of-the-art all-electric GEO satellite system design.

- A surrogate-based optimization method is utilized to reduce the computational cost of the satellite MDO problem. The total transfer time is reduced by **21.7%**, while the total mass yields a **66.1kg** decrease after optimization. The reduced mass leads to a lighter satellite with lower launch cost, and it could also be dedicated to additional payloads which means more revenue from customers' perspective.

- The optimization results illustrate that the proposed surrogate assisted MDO framework is feasible and effective to improve the quality and efficiency of all-electric GEO satellite system design. The work could be referred for further all-electric spacecraft system research. In future work, we will try to apply this proposed framework to other spacecraft systems design and optimization.

# Thank You