立方星地球电离层掩星探测

Cube-based Earth ionospheric occultation detection

Ionosphere Detection Based on CubeSat Occultation

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1.1 任务背景
Mission background

地球的大气按照电磁特性可以分为中性层、电离层和磁层。
The earth's atmosphere can be divided into neutral layer, ionosphere and magnetosphere according to its electromagnetic characteristics.

电离层结构可以用电离层特性参量来表征：电子密度、离子密度、电子温度、离子温度，其中电子密度是影响电磁波（如北斗信号）传播的主要参量，使得北斗定位时产生绝对测距误差。而电离层的时空变化受太阳周期性、非周期性活动影响，同时地球本身自然环境因素、地球磁场异常也对电离层的电磁特性有较大影响。上述原因使得电离层无法通过简单模型推演的方法进行预测，只能通过实时实地的观测才能得到有实际意义的结果。

The ionospheric structure can be characterized by ionospheric characteristic parameters: electron density, ion density, electron temperature and ion temperature, among which electron density is the main parameter affecting the propagation of electromagnetic waves (such as Beidou signals), resulting in absolute ranging errors in Beidou positioning. The temporal and spatial variations of the ionosphere are affected by the periodic and non-periodic activities of the sun, while the natural environmental factors of the earth itself and the anomalies of the earth's magnetic field also have a greater impact on the electromagnetic characteristics of the ionosphere. Because of the above reasons, the ionosphere can not be predicted by simple model deduction method, and only through real-time field observation can practical results be obtained.

利用立方星对北斗系统的掩星来进行电离层探测。
The ionosphere is detected by the occultation of Beidou system by Cubex.

1.2 任务约束及要求
Task constraints and requirements

7 天之内在规定的大气高度以下，实现的北斗掩星次数最多。
Within 7 days, the number of Beidou occultations is the largest below the specified atmospheric altitude.

电离层上界 Upper ionospheric boundary	电离层上界 Upper ionospheric boundary	任务时间 Mission time	性能指标 Performance indicators
700km	60km	7天 7 days	掩星次数 Number of occultations

1.3 任务分析
Mission analysis

先在 STK 中导入北斗系统 TLE，选择 20211221UTCG0400 开始 7 天，先随机设置一个轨道观察。

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Firstly, import the TLE of the Beidou system in the STK, select 20211221UTCG0400 for 7 days, and randomly set an orbit for observation.

具有如下性质：

Has the following properties:

1、GEO，IGSO 卫星占多数，且 IGSO 的分布较均匀，对于在低轨运行的卫星而言，轨道根数变化对于 GEO 和 IGSO 掩星次数影响不大。

1. GEO and IGSO satellites are in the majority, and the distribution of IGSO is relatively uniform. For satellites operating in low orbit, the change of orbit elements has little effect on the number of GEO and IGSO occultations.

2、MEO 分布在三条轨道，图中绿色为最多一条 MEO，倾角= 56.7317deg ，

2. MEO is distributed in three orbits. In the figure, there is at most one MEO in green, and the inclination angle is 56.7317 deg.

RAAN= 359.432deg，其对于掩星的贡献应该是最大。

RAAN = 359.432 deg, which should be the largest contribution to the occultation.

3、CubeSat 越靠近电离层上界，掩星概率越高，但在选定掩星次数为性能

3. The closer CubeSat is to the upper ionosphere, the higher the probability of occultation, but when the number of occultations is selected as the performance

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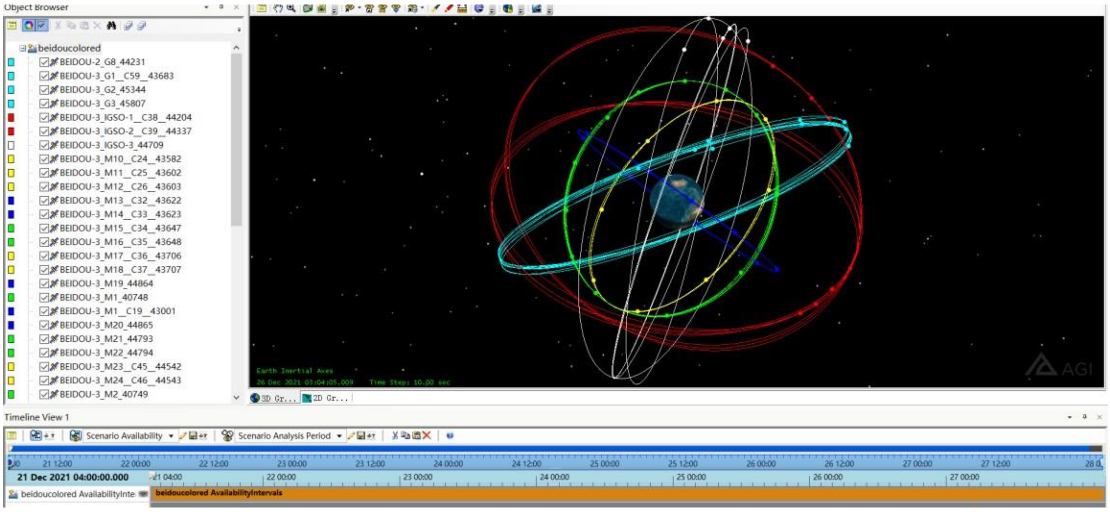
指标时，也不能太低。更多。因此不难想象，逆行轨道的掩星次数将会明显多于顺行轨道。

Indicators should not be too low. More. Therefore, it is not difficult to imagine that retrograde orbits will have significantly more occultations than prograde orbits.



1.4 MATLAB 仿真

MATLAB simulation

由于北斗轨道近圆，可以在MATLAB中设定为不考虑J2和其他摄动的预报模型进行仿真。

Because the Beidou orbit is nearly circular, it can be simulated in MATLAB without considering the prediction model of J2 and other perturbations.

将北斗TLE读入仿真程序，设定轨道倾角，轨道高度，升交点赤经为优化指标。由于顺行逆行搜索范围过大，故分为两种情况仿真。

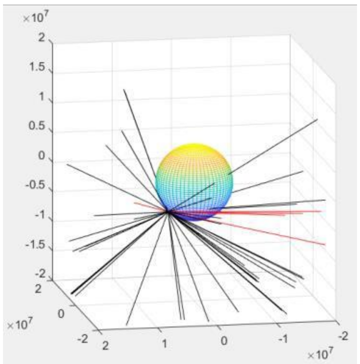
The Beidou TLE is read into the simulation program, and the orbit inclination, orbit height and ascending node right ascension are set as the optimization indexes. Because the anterograde and retrograde search range is too large, the simulation is divided into two cases.

设定好优化函数obscu.m，输入为轨道根数，输出为掩星次数，利用MATLAB自带遗传算法工具库进行优化，此时需要将掩星次数取倒数。在确定大致区间 后，扩展区间，再利用单纯形法，fminsearch函数进行进一步优化，最后带入

The optimization function obscu. M is set, that input is the orbit element, the output is the occultation times, the optimization is carry out by using the genetic algorithm tool library of MATLAB, and the occultation times need to be reciprocate at this time. After the approximate interval is determined, the interval is extended, and then the simplex method and the fminsearch function are used for further optimization, and finally the

STK验证。同时，将MATLAB的计算过程可视化，以便直观对比。

STK validation. At the same time, the calculation process of MATLAB is visualized for intuitive comparison.



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1.4.1 顺行轨道

Direct orbit

首先设定优化初值：

First, set the initial value of optimization:

	轨道倾角（deg） Orbital inclination (deg)	轨道高度（km） Track height (km)	RAAN（deg）
上界 Upper bound	0	700	0
下界 Lower bound	90	800	180

遗传算法优化结果为：

The optimization result of genetic algorithm is:

	轨道倾角（deg） Orbital inclination (deg)	轨道高度（km） Track height (km)	RAAN（deg）
Gaoptimize	75	710	120

扩展区间，使用fminsearch优化：

Expand the interval and optimize with fminsearch:

	轨道倾角（deg） Orbital inclination (deg)	轨道高度（km） Track height (km)	RAAN（deg）
上界 Upper bound	70	700	110
下界 Lower bound	80	720	130

优化结果：

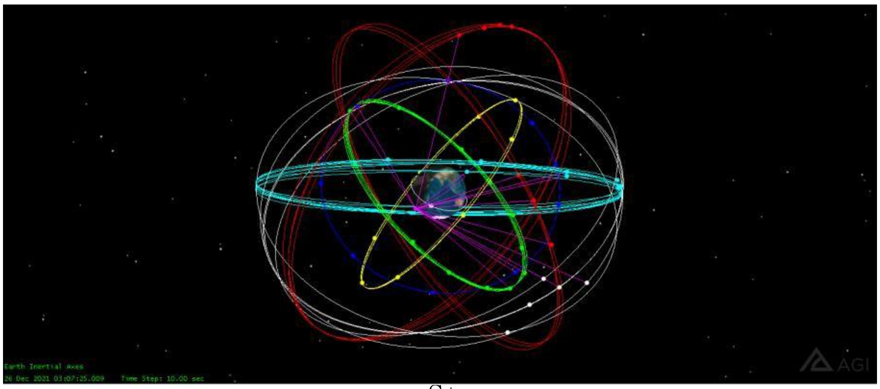
Optimization results:

	轨道倾角（deg） Orbital inclination (deg)	轨道高度（km） Track height (km)	RAAN（deg）	掩星次数 Number of occultations
fminsearch	78.32	702.3	115.2	10292

带入STK仿真得：

Carried over to STK simulation:

起始时间 Start time	轨道倾角（deg） Orbital inclination (deg)	轨道高度（km） Track height (km)	RAAN（deg）	掩星次数 Number of occultations
20211221UTCG0400	78.32	702.3	115.2	10083



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1.4.2 逆行轨道
Retrograde orbit

首先设定优化初值：
First, set the initial value of optimization:

	轨道倾角（deg） Orbital inclination (deg)	轨道高度（km） Track height (km)	RAAN（deg）
上界 Upper bound	90	700	0
下界 Lower bound	180	800	180

遗传算法优化结果为：
The optimization result of genetic algorithm is:

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	轨道倾角（deg） Orbital inclination（deg）	轨道高度（km） Track height（km）	RAAN（deg）
Gaoptimize	160	740	120

扩展区间，使用fminsearch优化：

Expand the interval and optimize with fminsearch:

	轨道倾角（deg） Orbital inclination（deg）	轨道高度（km） Track height（km）	RAAN（deg）
上界 Upper bound	150	730	110
下界 Lower bound	170	750	130

优化结果：

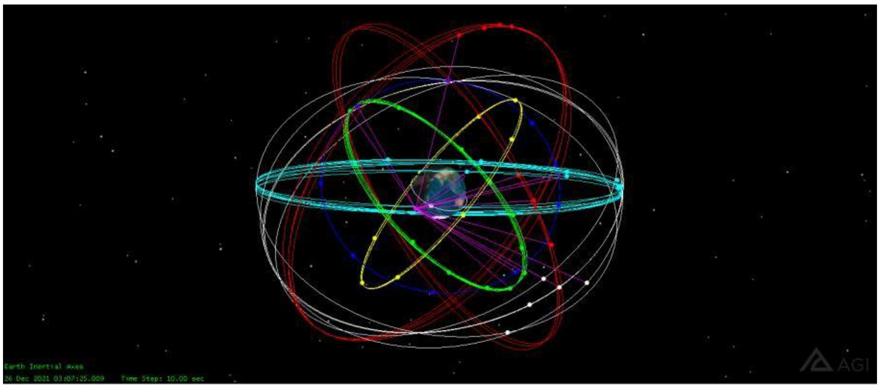
Optimization results:

	轨道倾角（deg） Orbital inclination (deg)	轨道高度（km） Track height（km）	RAAN（deg）	掩星次数 Number of occultations
fminsearch	162.2	739.21	122.76	12006

带入STK仿真得：

Carried over to STK simulation:

起始时间 Start time	轨道倾角（deg） Orbital inclination (deg)	轨道高度（km） Track height（km）	RAAN（deg）	掩星次数 Number of occultations
20211221UTCG0400	162.2	739.21	122.76	11196



1.4.3 多颗星

Multiple stars

题目还要求 4 颗 CUBESAT 同时在轨工作，导航卫星的布置准则基本按照均匀布置，其目的是为了使得建立链路/覆盖最大化，且服务能力相同，实际上也适用于该掩星任务。

The project also requires four CUBESATs to work in orbit at the same time, and the arrangement criteria of navigation satellites are basically in accordance with the uniform arrangement, the purpose of which is to maximize the establishment of links/coverage, and the service capability is the same, which is actually applicable to the occultation mission.

要求统一轨道卫星最近不少于 1000km，均匀分布是显然满足。对于顺行轨

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起始时间 Start time	轨道倾角 Orbital inclination（deg）	轨道高度 Orbital altitude（km）	RAAN（deg）	掩星次数 Number of occultations
20211221UTCG0400	78.32	702.3	115.2	10083

道，单颗星：

Uniform distribution is obviously satisfied by requiring the nearest satellite in uniform orbit to be not less than 1000 km. For a prograde orbit, a single star:

则每颗卫星的真近点偏差近似为：

Then the true anomaly of each satellite is approximately:

$$M = 90\,deg$$

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起始时间 Start time	轨道倾角 Orbital inclination (deg)	轨道高度 Orbital altitude (km)	RAAN (deg)	M (deg)
20211221UTCG0400	78.32	702.3	115.2	0
20211221UTCG0400	78.32	702.3	115.2	90
20211221UTCG0400	78.32	702.3	115.2	180
20211221UTCG0400	78.32	702.3	115.2	270

导入 STK，顺行 4cubesat 掩星次数 40257 次。

对于顺行轨道，单颗星：

STK was introduced, and the number of occultations of 4cubesat was 40257. For a prograde orbit, a single star:

起始时间 Start time	轨道倾角 Orbital inclination (deg)	轨道高度 Orbital altitude (km)	RAAN (deg)	掩星次数 Number of occultations
20211221UTCG0400	162.2	739.21	122.76	11196

则每颗卫星的真近点偏差近似为：

Then the true anomaly of each satellite is approximately:

$$M = 90\ deg$$

起始时间 Start time	轨道倾角 Orbital inclination (deg)	轨道高度 Orbital altitude (km)	RAAN (deg)	M (deg)
20211221UTCG0400	162.2	739.21	122.76	0
20211221UTCG0400	162.2	739.21	122.76	90
20211221UTCG0400	162.2	739.21	122.76	180
20211221UTCG0400	162.2	739.21	122.76	270

导入 STK，顺行 4cubesat 掩星次数 44755 次。

STK was introduced, and the number of occultations of 4cubesat was 44755.

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二、　卫星结构设计

Two、 Satellite structure design

2.1 卫星器件作用

Function of satellite device

2.1.1 星体结构

Stellar structure

与绝大多数航天器结构功能相同，承载其他设备，为星载设备提供符合条件的安装空间和精度，保持卫星的结构形状正常。

It has the same structural function as most spacecraft, carries other equipment, provides qualified installation space and accuracy for on-board equipment, and maintains the normal structural shape of the satellite.

分系统 Subsystem	功能 Function
姿轨控系统 Attitude and orbit control system	星敏相机通过对恒星位置的成像，将像输入到主板进行计算，从而得到姿态信息；磁力矩器通过电磁装置输出力矩进行姿态控制和 The star sensitive camera inputs the image to the main board for calculation by imaging the position of the star, thereby obtaining the attitude information; The magnetic torquer controls the attitude through the output torque of the electromagnetic device. 维持。 Maintenance.
有效载荷 Payload	对于本卫星而言，主相机是卫星的主载 荷，用于对地成像，包括可见光波段和红外波 For this satellite, the main camera is the main payload of the satellite, which is used to image the earth, including visible light band and infrared wave. 段。 Duan.
通讯系统 Communication system	通讯主板用于调制发射信号并分析所收信号， 并将相应指令传给星载计算机；天线机构用于 The communication main board is used for modulating a transmitting signal, analyzing a received signal and transmitting a corresponding instruction to the on-board computer; The antenna mechanism is used 接受和发送信号。 Receive and send signals.
太阳电池阵 Solar Array	主要包含太阳能电池，电线等电性器件和 Mainly comprises electrical devices such as solar cells, wires and the like, 基板，吸收太阳光照，为卫星提供电能。 The substrate absorbs sunlight and provides electric energy for the satellite.
电源系统 Power supply system	储存、分配太阳电池阵提供的电能，为星上其它一切用电元件提供符合电压、电流要求的电 力。 It stores and distributes the electric energy provided by the solar array, and provides the electric power meeting the requirements of voltage and current for all other electrical components on the satellite.
星载计算机 On-board computer	星载计算机用于处理星上的数据，并根据各种数据给出相应的指令。 The on-board computer is used to process the data on the satellite and give corresponding instructions according to various data.

2.2 卫星组装

Satellite Assembly

将提供的卫星零件组装后得到：

Assembling the supplied satellite parts yields:

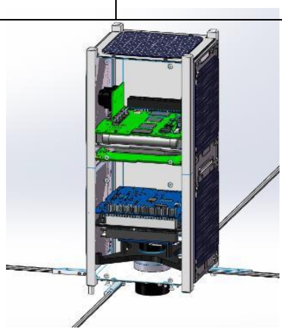

图 1 卫星内部装配

Figure 1 Satellite Internal Assembly

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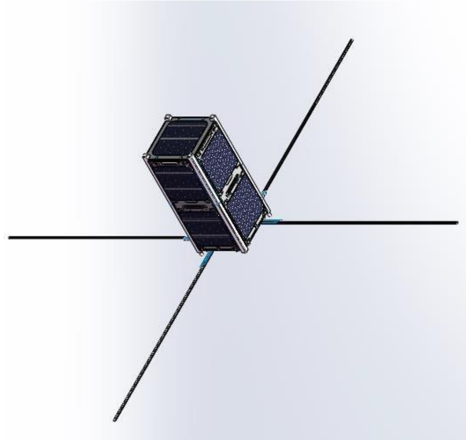

图 2 2U 小卫星组装图

Fig. 2 Assembly drawing of 2U small satellite

2.3 典型机械零件 Typical mechanical parts

本文选择了六角头螺栓、圆柱销和顶部太阳电池阵基板进行绘图，简要图如下，详细零件图见附页。

In this paper, the hexagon head bolt, cylindrical pin and top solar array substrate are selected for drawing. The brief drawing is as follows, and the detailed part drawing is shown in the attached page.

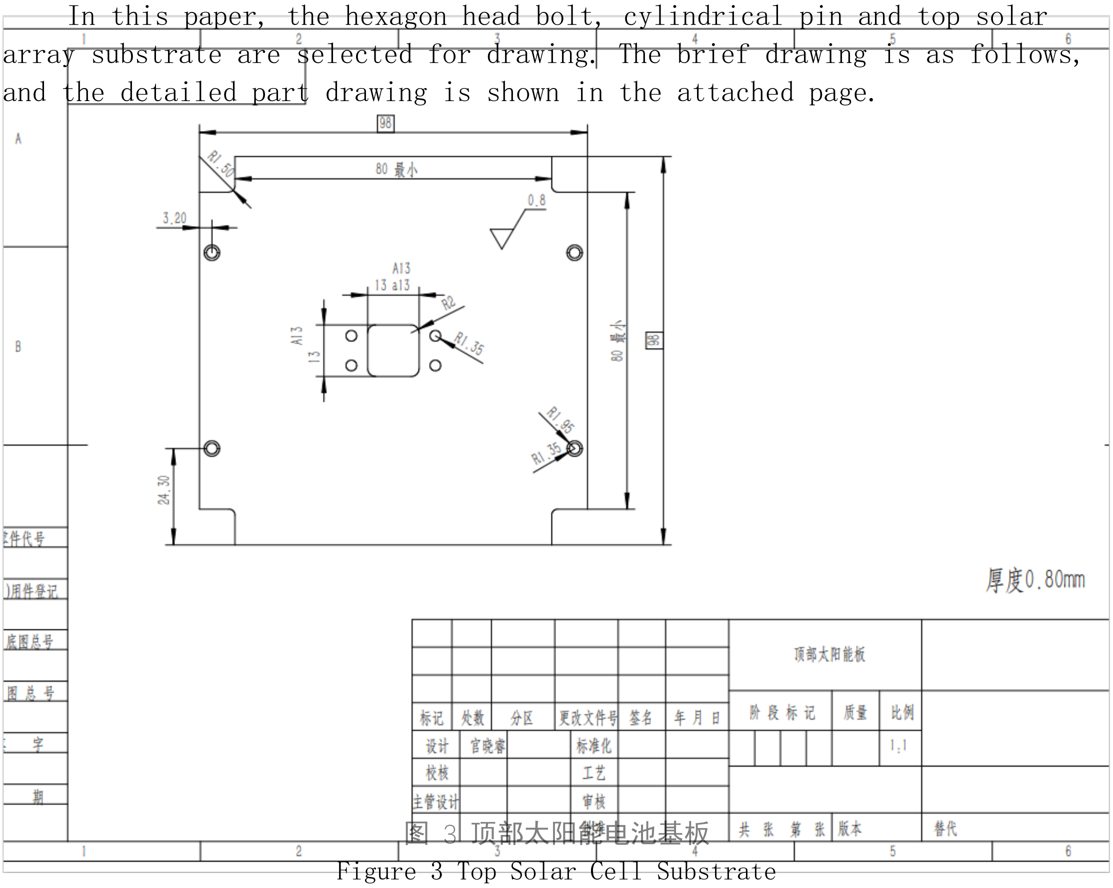

图 3 顶部太阳能电池基板

Figure 3 Top Solar Cell Substrate

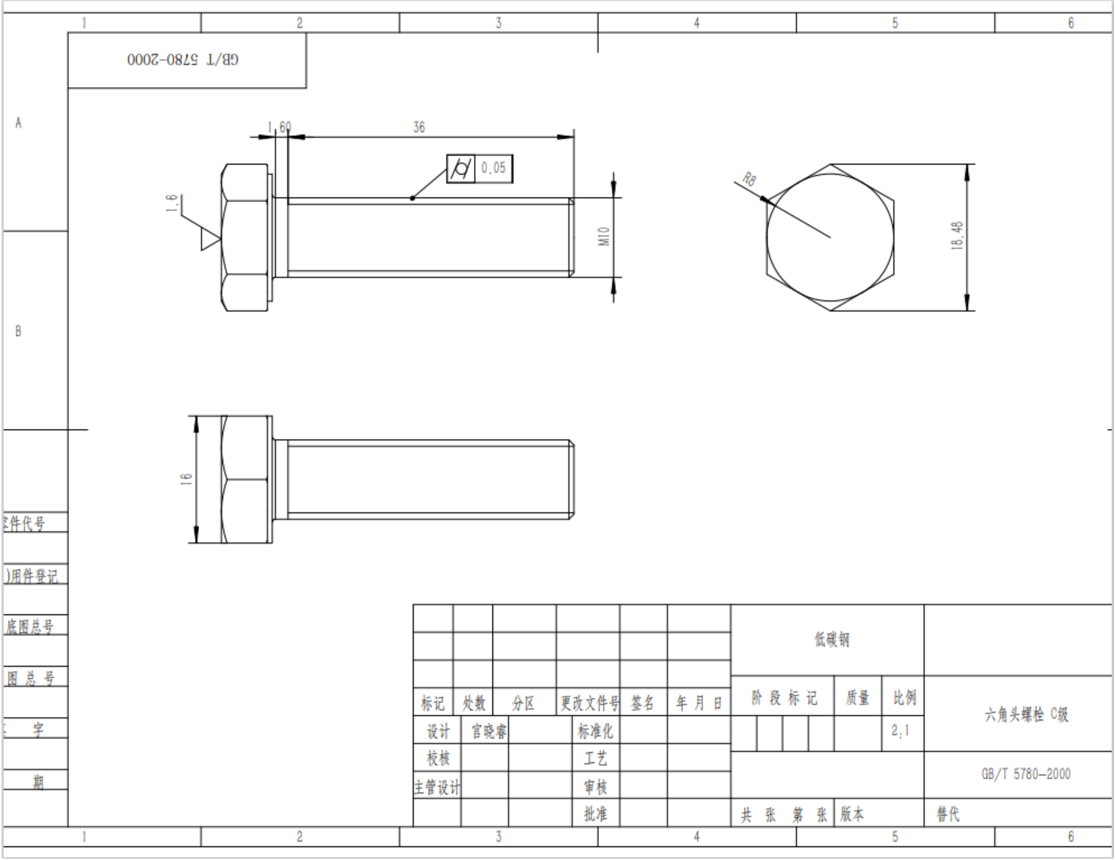

图 4 六角头螺栓

Fig. 4 Hexagon-head bolt

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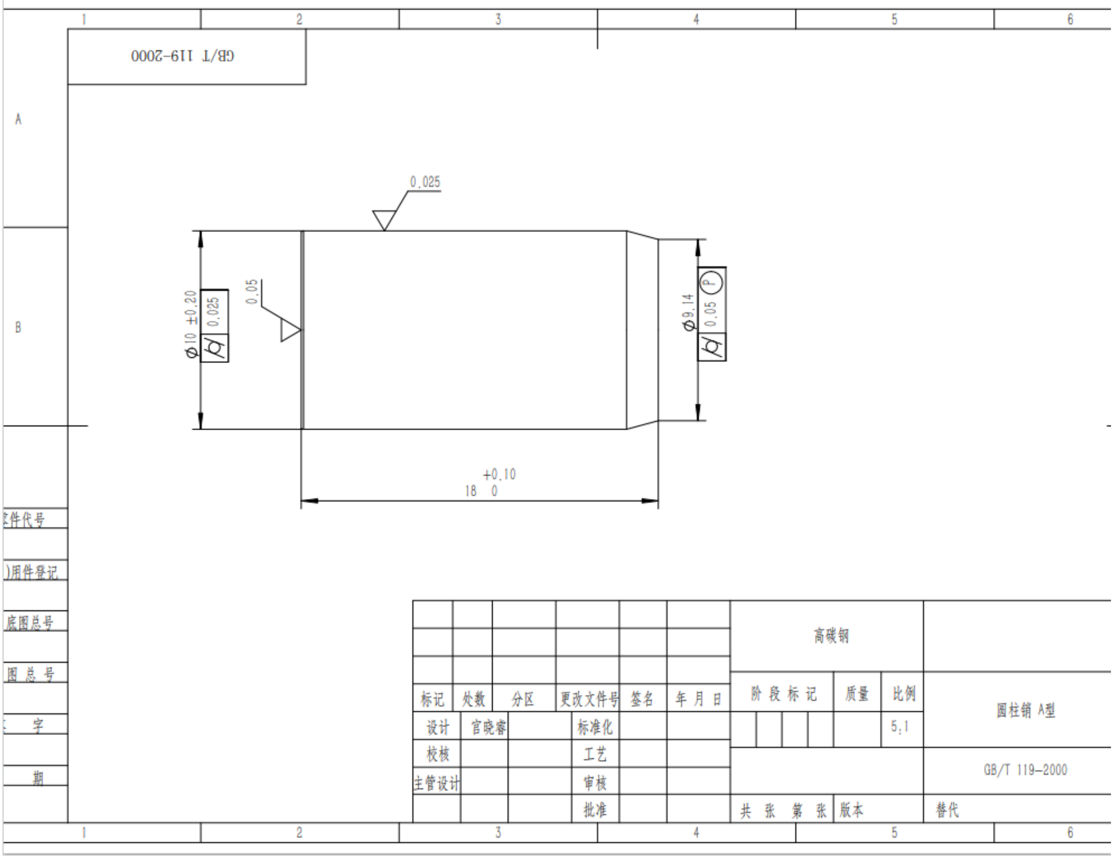

图 5 六角头螺栓

Fig. 5 Hexagon-head bolt

三、 卫星结构分析

III. Satellite Structure Analysis

3.1 任务说明
Mission statement

对于 2Ucubesat 的装配体模型进行合理简化，分析三种过载情况下的应力应变，进行结构的模态分析，得到结构的前十阶模态频率以及振型。根据分析结果进行修改再分析。

The assembly model of 2Ucubesat is reasonably simplified, and the stress and strain under three overload conditions are analyzed. The modal analysis of the structure is carried out, and the first ten modal frequencies and mode shapes of the structure are obtained. According to the analysis results, the modification and reanalysis are carried out.

3.2 建模过程
Modeling process

基于装配体模型结构，使用 solidworks 建模并导入，按照给定要求进行材料、密度等设置，直接得到模型，导入 ANSYS 仿真，具体模型如下图。

Based on the assembly model structure, use solidworks to model and import, set the material and density according to the given requirements, directly obtain the model, and import it into ANSYS simulation. The specific model is shown in the following figure.

3.3 模态分析
Modal analysis

通过模态分析得到了结构的前十阶固有频率以及振型：
The first ten natural frequencies and mode shapes of the structure are obtained by modal analysis.

阶数 Order	1	2	3	4	5
固有频率 Natural frequency	0.	0.	0.	5.2287e-3	1.0282e-2
阶数 Order	6	7	8	9	10
固有频率 Natural frequency	1.2201e-2	2018.7	2163.7	2250.4	2909.

表 1 各阶数固有频率

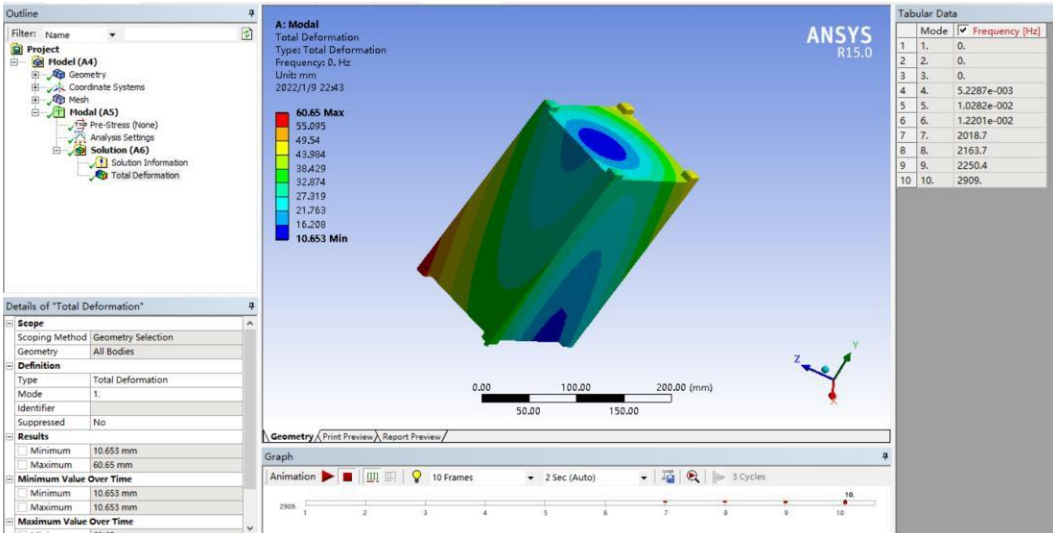

Table 1 Natural frequency of each order

图 6 前十阶模态

Fig. 6 First ten modes

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3.4 静力学分析

Static analysis

建立x_t 文件，导入 ANSYS，同时打开 Static Structural 分析模块，将卫星整体设置为铝材 Aluminium，上层基板，侧基板，天线设置为面板材料 Plane。

材料	弹性模量Gpa	泊松比	密度kg/m3	结构部位
铝	70	0.3	2700	主承力框架、侧板
其他	20	0.3	1000	层板及其他组件

Create an X _ t file, import it into ANSYS, open the Static Structural analysis module, and set the whole satellite as Aluminium, the upper substrate, the side substrate, and the antenna as Plane.

表 2 材料性能

Table 2 Material Properties

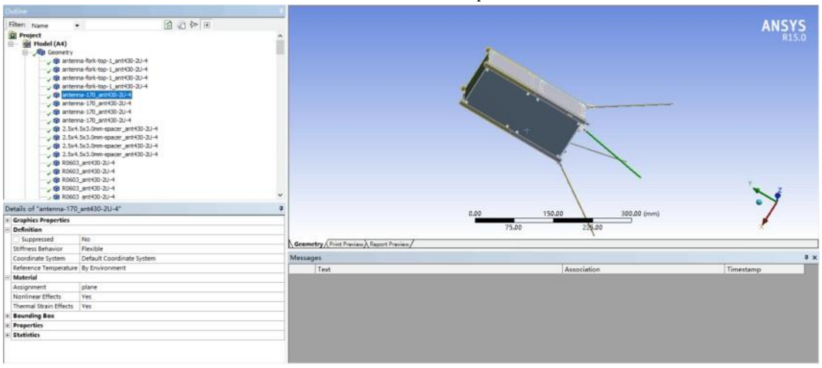

图 7 设置天线

Figure 7 Setting up the antenna

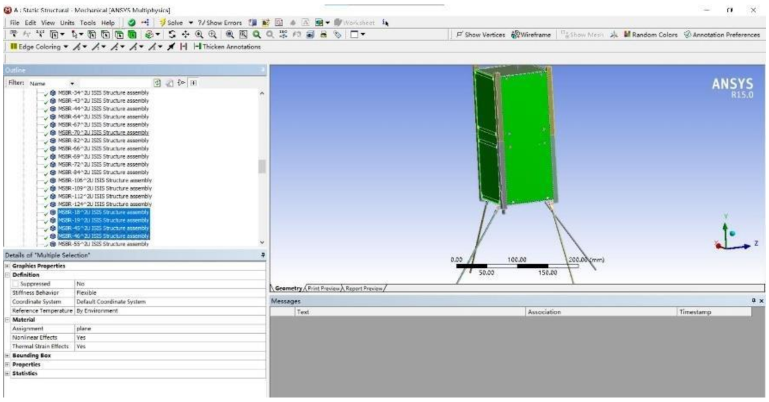

图 8 设置侧面面板

Figure 8 Setting the side panel

按照题目要求加载荷:

Load according to the requirements of the title:

工况 1：纵向（X 方向）过载 6.6g

Working condition 1: longitudinal (X direction) overload 6.6g

工况 2：横向过载（Y、Z 方向）1.2g

Working condition 2: lateral overload (Y, Z direction) 1.2g

工况 3：组合过载 (X 6.6g, Y 1.2g, Z 1.2g)

Condition 3: Combined overload (X 6.6g, Y 1.2g, Z 1.2g)

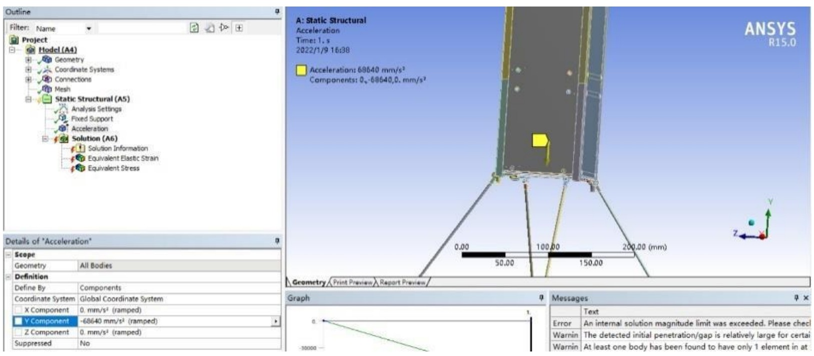

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表 3设置过载
Table 3 Set Overload

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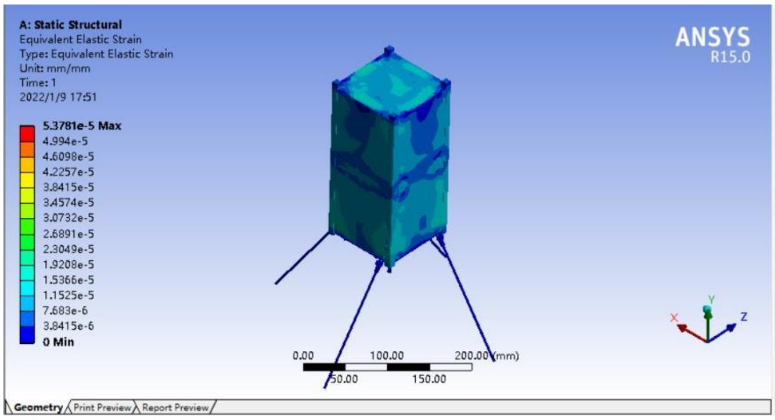
3.4.1 工况 1

Condition 1

纵向（X 方向）过载 6.6g



Longitudinal (X direction) overload 6.6g

图 9 工况 1 变形云图

Fig. 9 Deformation Nephogram of Working Condition 1

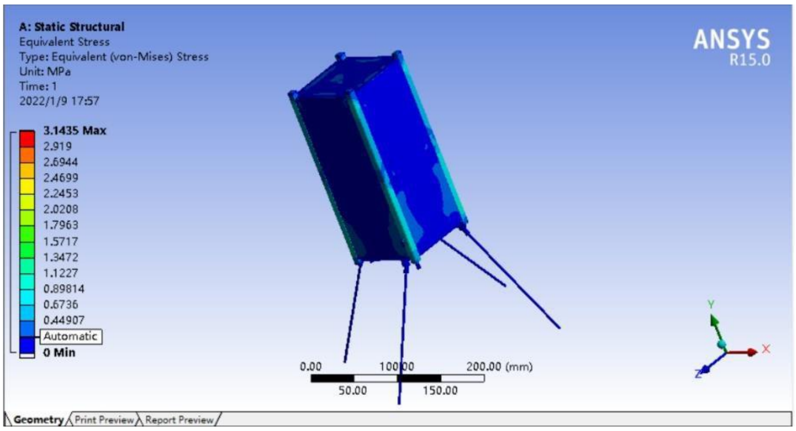


图 10 工况 1 过载云图

Fig. 10 Overload Cloud Chart of Working Condition 1

该工况下最大应变为 5.3781e-05，最大应力为 3.1435MPa。

Under this condition, the maximum strain is 5. 3781e-05, and the maximum stress is 3. 1435 MPa.

3.4.2 工况 2

Condition 2

横向过载 （Y、Z 方向）1.2g

Lateral overload (Y, Z direction) 1.2g

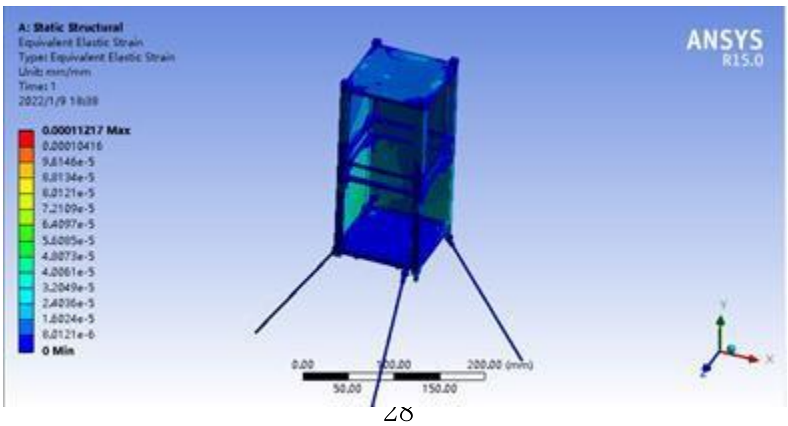


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图 11 工况 2 变形云图
Fig. 11 Deformation Nephogram of Working Condition 2

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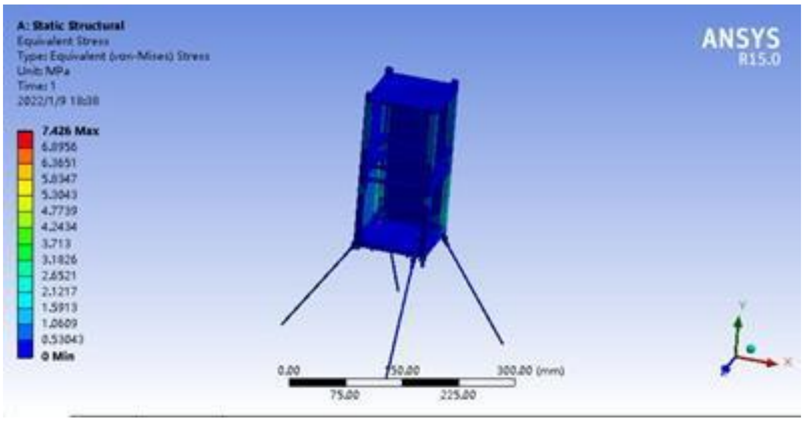

图 12 工况 2 应力云图

Fig. 12 Stress Nephogram under Working Condition 2

该工况下，最大应变为 1.11217e-4，最大应力为 7.426MPa

Under this condition, the maximum strain is 1, the 11217 is e-4, and the maximum stress is 7. 426 MPa

3.4.3 工况 3：

Working condition 3:

组合过载（X 6.6g, Y 1.2g, Z 1.2g）

Combined Overload (X 6.6g, Y 1.2g, Z 1.2g)

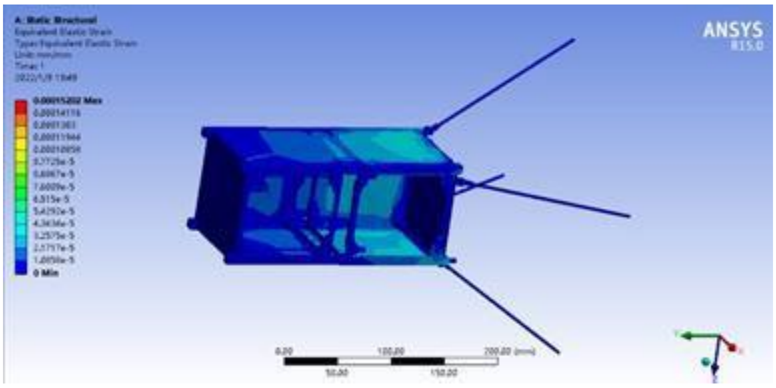

图 13 工况 3 变形云图

Fig. 13 Deformation Nephogram under Working Condition 3

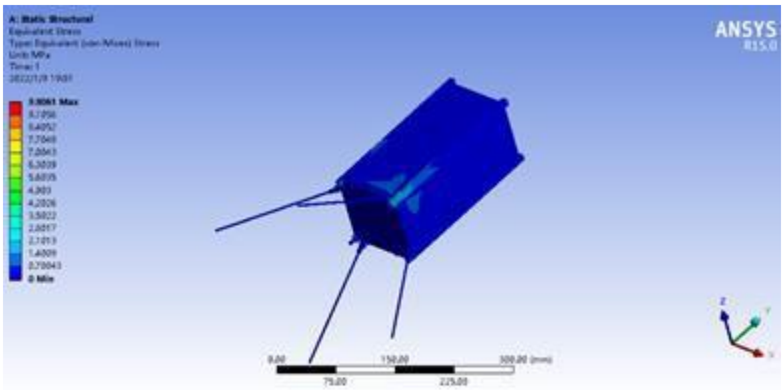

图 14 工况 3 应力云图

Fig. 14 Stress Nephogram under Working Condition 3

该工况下，最大应变为 1.5582e-04，最大应力为 9.8801MPa

Under this condition, the maximum strain is 1.5582e-04, and the maximum stress is

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9.8801 MPa

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四、 电源分系统
IV. Power supply subsystem

4.1 电源任务系统描述
Power Task System Description

CubeSat 工作模式中，
In the CubeSat operating mode,

（1） 基本模式：星载计算机+测控收发机=5.0W；
Basic mode: on-board computer + TT & C transceiver = 5.0 W;

（2） 对日指向模式：星载计算机+测控收发机+姿控部件=11.0W，在地影区，姿控部件不工作；

Sun-pointing mode: on-board computer + TT & C transceiver + attitude control unit = 11.0 W, in the shadow area, the attitude control unit does not work;

（3） 载荷操作模式（对日指向+载荷工作（载荷工作 15 分钟））：星载计算机+测控收发机+姿控部件+有效载荷=18.0W，在地影区，姿控部件正常工作，有效载荷正常工作；

Load operation mode (pointing to the sun + load operation (load operation for 15 minutes)): on-board computer + TT & C transceiver + attitude control unit + payload = 18.0 W. In the earth shadow area, the attitude control unit works normally and the payload works normally;

计算一年 12 个月中不同的位置，找出电源供应最不足的一个月。
Calculate the locations for each of the 12 months of the year to find the month with the lowest power supply.

根据模式（1）、(2)(3) 的要求分别进行分析、仿真、计算，给出分析结论，作为轨道设计的约束。

According to the requirements of modes (1), (2) and (3), the analysis, simulation and calculation are carried out respectively, and the analysis conclusion is given as the constraint of track design.

4.2 电源任务系统描述
Power Task System Description

4.2.1 卫星需求功率计算
Satellite demand power calculation

太阳电池阵满足卫星需求，应至少产生的功率输出为
The solar array shall meet the satellite requirements and shall generate a minimum power output of

$$P_{sa}=\frac{\frac{P_eT_e}{X_e}+\frac{P_dT_d}{X_d}}{T_d}$$

P_e——星上设备地影区平均功耗；
— — average power consumption of satellite equipment in earth shadow area;

P_d——星上设备光照区平均功耗；

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— — average power consumption of on-board equipment in illumination area;

T_e——地影区时间；
-time of earth shadow area;

T_d——光照区时间；
— — time of illumination area;

X_e——太阳电池阵经蓄电池组到载荷的输出效率；
— — output efficiency of the solar array to the load through the battery pack;

X_d——太阳电池阵到载荷的输出效率。
— — output efficiency from solar array to load.

4.2.2 太阳电池阵初期功率计算
Calculation of initial power of solar array

确定卫星寿命初期，太阳电池阵单位面积功率输出为
It is determined that the power output per unit area of the solar array at the beginning of the satellite life is

$$P_{BOL} = S \times \eta_{SC} \times AVE\{\sum_{n=1}^{4} cos\theta_n\} \times I_d$$

S——太阳照度常数1368W/m²；
-Solar illumination constant 1368 W/m²;

η_{SC}——太阳电池片效率；
-solar cell efficiency;

θ_n——太阳矢量与 4 个太阳电池阵列的法线的夹角；
— — the angle between the solar vector and the normal of the four solar cell arrays;

I_d——过滤因子，取0.75。
-Filtration factor, 0.75.

其中，太阳能电池片新的时候效率η_{SC} = 25%，$AVE\{\sum_{n=1}^{4} \cos\theta_n\}$取经验值
Wherein, when the solar cell is new, the efficiency = 25%, $\{\sum_{n=1}^{4} Cos\}$ takes the empirical value

0.92。

4.2.3 太阳电池阵末期功率计算
Calculation of Solar Array Power at the End of Life

计算卫星寿命末期，太阳电池阵单位面积功率输出为
The power output per unit area of the solar array at the end of the satellite life is calculated as

$$P_{EOL} = P_{BOL} \times L_d$$

其中，太阳电池片降级因子
Wherein the degradation factor of the solar cell

$$L_d = \eta_{uv} \times \eta_{tc} \times \eta_m \times \eta_r \times \eta_{con} \times \eta_s \times \eta_{rad} \times \eta_t \times \eta_{op}$$

η_{uv}——紫外线引起的功率损失，取0.98；
— — power loss caused by ultraviolet ray, 0.98;

η_{tc}——热循环引起的功率损失，取0.99；
— — power loss caused by thermal cycle, 0.99;

η_m——电池片不匹配引起的功率损失，取0.975；
— — Power loss caused by mismatching of cells, 0.975;

η_r——电池片内阻引起的功率损失，取0.98；
— — power loss caused by internal resistance of cell, 0.98;

η_{con}——外部污染源引起的功率损失，取0.99；
— — power loss caused by external pollution source, 0.99;

η_s——外部遮挡引起的功率损失，取1；
— — power loss caused by external shading, taken as 1;

η_{rad}——辐射损伤引起的功率损失$\eta_{rad} = (1 - 2.75\%)^{lifetime}$，其中$GaAs$电池每年性能下降

2.75%；

— — power loss due to radiation damage = (1 − 2.75%) , where the performance of the battery is reduced by 2.75% per year;

η_t——操作温度调节损失，卫星四面电池阵温度变化范围$-90 \sim +95°C$正常

— — Loss of operating temperature regulation, and the temperature change range of the satellite four-side battery array is − 90 ~ + 95°.

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测试温度25°C，故$\eta_t = 1 - 0.0017 \times (95 - 25) = 0.88$；
Test temperature 25°, so = 1 − 0.0017 × (95 − 25) = 0.88;

η_{op}——在轨道位置太阳照度常数调节，取1。
-adjustment of solar illumination constant at orbital position, taken as 1.

4.2.4 太阳电池阵最小面积计算
Calculation of minimum area of solar array

计算在卫星寿命末期，太阳电池阵所需要的面积
Calculate the area required for the solar array at the end of the satellite's life

$$A'_{SA} = P_{SA}/P_{EOL}$$

4.2.5 太阳电池阵最大输出功率计算
Calculation of maximum output pow of solar array

计算在卫星寿命初期，太阳电池阵输出的功率
Calculate the output power of the solar array at the beginning of the satellite's life

$$P = P_{BOL} \times A'_{SA}$$

4.2.6 评估太阳电池阵面积
Assessing solar array area

评估实际的太阳电池阵面积是否满足要求，若
Evaluate whether the actual solar array area meets the requirements, if

$$A_{SA} > A'_{SA}$$

成立，则太阳电池阵满足设计要求。
The solar array meets the design requirements.

4.2.7 蓄电池组计算
Battery pack calculation

蓄电池组要求的容量估算
Capacity estimation required for storage battery

$$C' = 1.2 \times \frac{P_e T_e}{DOD \times \eta \times N \times V_{bus}}$$

4.3 设计实施
Design and implementation

CubeSat 卫星结构为 2U 单元卫星，除朝向地球的一面外，其余表面均可加
CubeSat satellite structure is a 2U unit satellite, which can be added on all surfaces except the side facing the earth.

装太阳能电池片。电池片总面积可以达到
Install solar cells. The total area of the cell can reach

$$A_{SA} = 0.1 \times 0.1 \times (2 \times 4 + 1) = 0.09m^2$$

卫星的寿命预计为一年。太阳能电池阵选择$GaAs$电池。蓄电池组选择锂离子电池组，相关参数如表 4-1 所示。

The life of the satellite is expected to be one year. The solar array selects

类型 Type	放电深度 Depth of discharge	容量 Capacity	每组电池数 Number of batteries per group	最大电压 Maximum voltage	正常电压 Normal voltage
锂离子电池组 Lithium ion battery pack	30%	3Ah	3	4.1V	3.6V

the cells. The lithium-ion battery pack is selected for the battery pack, and the relevant parameters are shown in Table 4-1.

表 4 锂离子蓄电池组参数

Table 4 Parameters of Lithium Ion Battery Pack

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则相关参数取为

Then the relevant parameters are taken as

$$X_e = 0.70$$
$$X_d = 0.85$$

根据第 3 章中得到的最优轨道，可知 CubeSat 在日照区和阴影区总时长，如下表所示：

According to the optimal orbit obtained in Chapter 3, the total duration of CubeSat in the sunshine area and the shadow area is shown in the following table:

月份 Month Share	光照区/sec Illuminated area/sec	半影区 Penumbra /sec	全影区/sec Full Shadow Area/sec	阴影区/sec Shaded area/sec	净光照/sec Net light/sec	单日平均净光照/sec Daily average net Light/sec
1	1779442.758	9607.542	888001.105	897608.647	881834.111	28446.26165
2	1992087.982	27278.334	399913.005	427191.339	1564896.643	55889.16582
3	1766011.793	9064.235	902706.853	911771.088	854240.705	27556.15177
4	1904987.007	34240.674	649367.155	683607.829	1221379.178	40712.63927
5	1719449.268	17383.76	945901.786	963285.546	756163.722	24392.37813
6	1826994.738	10035.652	752602.017	762637.669	1064357.069	35478.56897
7	2317567.57	11360.442	351972.142	363332.584	1954234.986	63039.83826
8	1767103.652	8937.519	901208.136	910145.655	856957.997	27643.80636
9	2158014.225	10602.743	425365.132	435967.875	1722046.35	57401.545
10	1897868.041	12950.257	632595.124	645545.381	1252322.66	40397.50516
11	1916732.049	9361.87	798881.982	808243.852	1108488.197	36949.60657
12	1698253.326	15660.063	964824.337	980484.4	717768.926	23153.83632

表 5 CubeSat 卫星一年日照情况

Table 5 Annual sunshine condition of CubeSat satellite

为了排除天数对于净光照的影响，本文将净光照除以该月天数。可以看出，

In order to exclude the effect of the number of days on the net light, the net light is divided by the number of days in the month. As can be seen,

12 月份的数值最低，判断 12 月份为光照供应最不足的月份，参数即从 12 月选取，即

The value of December is the lowest, and it is judged that December is the month with the most insufficient light supply. The parameter is selected from December, that is,

$$T_e = 980484.4s$$
$$T_d = 1698253.326s$$

4.3.1 基本模式设计 Basic pattern design

在基本工作模式下，星载计算机和测控收发机在日照区和地影区均工作。则

In the basic working mode, the on-board computer and the TT & C transceiver work in both the sunshine area and the earth shadow area. Then

可得

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$$P_e = P_d = 5.0W$$

太阳电池阵满足卫星需求，应至少产生的功率输出为

The solar array shall meet the satellite requirements and shall generate a minimum power output of

$$P_{SA} = \frac{\frac{P_e T_e}{X_e} + \frac{P_d T_d}{X_d}}{T_d} = \frac{\frac{5.0 \times 980484.4}{0.70} + \frac{4.0 \times 1698253.326}{0.85}}{1698253.326} = 8.8298W$$

确定卫星寿命初期太阳电池阵单位面积功率输出为
The power output per unit area of the solar array at the initial stage of the satellite life is determined as

$$P_{BOL} = S \times \eta_{SC} \times AVE\{\sum_{n=1}^{4} \cos\theta_n\} \times I_d = 1368 \times 0.25 \times 0.92 \times 0.75$$
$$= 235.98\mathrm{W/m^2}$$

计算卫星寿命末期太阳电池阵单位面积功率输出为
The power output per unit area of the solar array at the end of the satellite life is calculated as

$$P_{EOL} = P_{BOL} \times L_d$$
$$= 235.98 \times 0.98 \times 0.99 \times 0.975 \times 0.98 \times 0.99 \times 1 \times 0.9725 \times 0.88$$
$$\times 1 = 185.342\mathrm{W/m^2}$$

计算在卫星寿命末期太阳电池阵所需要的面积
Calculate the area required for the solar array at the end of the satellite's life

$$A'_{SA} = P_{SA} / P_{EOL} = \frac{8.8298}{183.342} = 0.04816m^2$$

计算在卫星寿命初期太阳电池阵输出的功率
Calculating the output power of the solar array at the beginning of the satellite's life

$$P = P_{BOL} \times A'_{SA} = 235.98 \times 0.04816 = 11.365W$$

评估实际的太阳电池阵面积是否满足要求，由于
Evaluate whether the actual solar array area meets the requirements, because

$$A_{SA} = 0.09m^2 > A'_{SA} = 0.04816m^2$$

此太阳电池阵满足基本工作模式设计要求。
The solar array meets the design requirements of the basic working mode.

蓄电池组要求的容量估算
Capacity estimation required for storage battery

$$C' = 1.2 \times \frac{P_e T_e}{DOD \times \eta \times N \times V_{bus}} = 1.2 \times \frac{5.0 \times 980484.4}{0.3 \times 0.25 \times 3 \times 3.6} = 7262847.407C$$

4.3.2 对日指向模式设计 Design of pointing mode to the sun

在对日指向模式下，星载计算机和测控收发机在日照区和地影区均工作。而
In the sun pointing mode, the on-board computer and the TT & C transceiver work in both the sunshine area and the earth shadow area. And

姿控只在地影区外工作，则可得
If the attitude control only works outside the earth shadow area,

$$P_e = 5W$$
$$P_d = 11W$$

太阳电池阵满足卫星需求，应至少产生的功率输出为
The solar array shall meet the satellite requirements and shall generate a minimum power output of

$$P_{SA} = \frac{\frac{P_e T_e}{X_e} + \frac{P_d T_d}{X_d}}{T_d} = \frac{\frac{5 \times 980484.4}{0.70} + \frac{11 \times 1698253.326}{0.85}}{1698253.326} = 17.065W$$

确定卫星寿命初期太阳电池阵单位面积功率输出为

The power output per unit area of the solar array at the initial stage of the satellite life is determined as

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$$P_{BOL} = S \times \eta_{SC} \times AVE\{\sum_{n=1}^{4} \cos\theta_n\} \times I_d = 1368 \times 0.25 \times 0.92 \times 0.75$$
$$= 235.98\mathrm{W/m^2}$$

计算卫星寿命末期太阳电池阵单位面积功率输出为

The power output per unit area of the solar array at the end of the satellite life is calculated as

$$P_{EOL} = P_{BOL} \times L_d$$
$$= 235.98 \times 0.98 \times 0.99 \times 0.975 \times 0.98 \times 0.99 \times 1 \times 0.9725 \times 0.88 \times 1 = 185.342\mathrm{W/m^2}$$

计算在卫星寿命末期太阳电池阵所需要的面积

Calculate the area required for the solar array at the end of the satellite's life

$$A'_{SA} = P_{SA} / P_{EOL} = \frac{17.065}{183.342} = 0.0931m^2$$

计算在卫星寿命初期太阳电池阵输出的功率

Calculating the output power of the solar array at the beginning of the satellite's life

$$P = P_{BOL} \times A'_{SA} = 235.98 \times 0.0931 = 21.96W$$

评估实际的太阳电池阵面积是否满足要求，由于

Evaluate whether the actual solar array area meets the requirements, because

$$A_{SA} = 0.09m^2 < A'_{SA} = 0.0931m^2$$

此太阳电池阵**不满足**基本工作模式设计要求。

This solar array does not meet the design requirements of the basic operation mode.

由于载荷功率过大，同时采用其他渠道提升发电功率或者降低载荷功率的方法不满足题设，所以考虑采用发电效率更高的太阳能电池阵。考虑将太阳能电池阵效率改为达到 30%。

Because the load power is too large, and the method of using other channels to increase the power generation or reduce the load power does not meet the design, it is considered to use a solar array with higher power generation efficiency. Consider changing the efficiency of the solar array to 30%.

确定卫星寿命初期太阳电池阵单位面积功率输出为

The power output per unit area of the solar array at the initial stage of the satellite life is determined as

$$P_{BOL} = S \times \eta_{SC} \times AVE\{\sum_{n=1}^{4} \cos\theta_n\} \times I_d = 1368 \times 0.35 \times 0.92 \times 0.75$$
$$= \mathbf{320.95}\mathrm{W/m^2}$$

计算卫星寿命末期太阳电池阵单位面积功率输出为

The power output per unit area of the solar array at the end of the satellite life is calculated as

$$P_{EOL} = P_{BOL} \times L_d$$
$$= 283.176 \times 0.98 \times 0.99 \times 0.975 \times 0.98 \times 0.99 \times 1 \times 0.9725 \times 0.88 \times 1 = 253.061\mathrm{W/m^2}$$

计算在卫星寿命末期太阳电池阵所需要的面积

Calculate the area required for the solar array at the end of the satellite's life

$$A'_{SA} = P_{SA} / P_{EOL} = \frac{17.065}{253.06} = 0.067433 m^2$$

计算在卫星寿命初期太阳电池阵输出的功率

Calculating the output power of the solar array at the beginning of the satellite's life

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$$P = P_{BOL} \times A^{'}_{SA} = 330.372 \times 0.086989 = 28.739W$$

评估实际的太阳电池阵面积是否满足要求，由于

Evaluate whether the actual solar array area meets the requirements, because

$$A_{SA} = 0.09m^2 > A^{'}_{SA} = 0.086989m^2$$

此太阳电池阵满足基本工作模式设计要求。

The solar array meets the design requirements of the basic working mode.

蓄电池组要求的容量估算

Capacity estimation required for storage battery

$$C^{'} = 1.2 \times \frac{P_e T_e}{DOD \times \eta \times N \times V_{bus}} = 1.2 \times \frac{11 \times 980484.4}{0.3 \times 0.35 \times 3 \times 3.6} = 11413045.93C$$

4.3.3 载荷操作模式设计 Load operation mode design

在载荷操作模式下，星载计算机和测控收发机在日照区和地影区均工作，该部分功率为11W。有效载荷功率为$7W$，在卫星的一个运行周期内，工作时间为15min。从 STK 软件得知 CubeSat 运行周期为5936.436s。由于有效载荷在光照去和阴影区都可以工作，可以将其间断工作模式等效为连续工作模式，并计算相

In the load operation mode, the on-board computer and TT & C transceiver work in both the sunshine area and the earth shadow area, and the power of this part is 11 W. The payload power is 7. 7, and the working time is 15 minutes in one operation cycle of the satellite. It is known from STK software that the CubeSat operation cycle is 5936.436 s. Since the payload can operate in both the illuminated and shaded regions, its discontinuous mode of operation can be equated to a continuous mode of operation, and the phase can be calculated

应的等效功率可得

The equivalent power should be available

$$P_e = P_d = 11 + \frac{7 \times 15 \times 60}{5936.436} = 12.0612W$$

太阳电池阵满足卫星需求，应至少产生的功率输出为（考虑到太阳电池阵升

The solar array shall produce a minimum power output of (taking into account the solar array liters) to meet the satellite demand

级，常数有所变化）

Level, the constant is changed)

$$P_{SA} = \frac{\frac{P_e T_e}{X_e} + \frac{P_d T_d}{X_d}}{T_d} = \frac{\frac{12.0612 \times 980484.4}{0.75} + \frac{12.0612 \times 1698253.326}{0.9}}{1698253.326} = 22.686W$$

确定卫星寿命初期太阳电池阵单位面积功率输出为

The power output per unit area of the solar array at the initial stage of the satellite life is determined as

$$P_{BOL} = S \times \eta_{SC} \times AVE\left\{\sum^{4} \cos\theta_n\right\} \times I_d = 1368 \times 0.35 \times 0.92 \times 0.75$$

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$$n=1$$
$$= 330.372\mathrm{W/m^2}$$

计算卫星寿命末期太阳电池阵单位面积功率输出为

The power output per unit area of the solar array at the end of the satellite life is calculated as

$$P_{EOL} = P_{BOL} \times L_d$$
$$= 235.98 \times 0.98 \times 0.99 \times 0.975 \times 0.98 \times 0.99 \times 1 \times 0.9725 \times 0.88 \times 1 = 253.065\mathrm{W/m^2}$$

计算在卫星寿命末期太阳电池阵所需要的面积

Calculate the area required for the solar array at the end of the satellite's life

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$$A'_{SA} = P_{SA} / P_{EOL} = \frac{22.686}{253.065} = 0.089644m^2$$

计算在卫星寿命初期太阳电池阵输出的功率

Calculating the output power of the solar array at the beginning of the satellite's life

$$P = P_{BOL} \times A'_{SA} = 330.372 \times 0.089644 = 29.6159W$$

评估实际的太阳电池阵面积是否满足要求，由于

Evaluate whether the actual solar array area meets the requirements, because

$$A_{SA} = 0.09m^2 > A'_{SA} = 0.089644m^2$$

此太阳电池阵满足基本工作模式设计要求。

The solar array meets the design requirements of the basic working mode.

蓄电池组要求的容量估算

Capacity estimation required for storage battery

$$C' = 1.2 \times \frac{P_e T_e}{DOD \times \eta \times N \times V_{bus}} = 1.2 \times \frac{12.0612 \times 980484.4}{0.3 \times 0.35 \times 3 \times 3.6} = 125140935.928C$$

4.4 结论与分析 Conclusion and analysis

从上节计算过程可以看出，选择了光照条件最差的 9 月进行仿真计算，基本模式、对日指向模式、载荷模式三种模式需要的太阳能电池阵最小面积分别为$0.04816m^2$，$0.086989m^2$，$0.089644m^2$。而 2U 的 CubeSat 卫星表面可装太阳能电池阵最大面积为$0.09m^2$，均可满足三种工作模式。蓄电池组的容量以13000000C为宜。

It can be seen from the calculation process in the previous section that September with the worst illumination condition is selected for simulation calculation, and the minimum area of solar array required for the basic mode, solar pointing mode and load mode is $0.4816^2$for 04816, $0.086989^2$for 086989, and $0.89644^2$for 089644, respectively. The maximum area of the solar array on the surface of the 2U CubeSat satellite is 0.0909^2, which can meet three working modes. The capacity of the storage battery should be 13000000 C.

考虑到固定于卫星表面的太阳能电池板的面积是不可变的，故有效优化为：

Considering that the area of the solar panel fixed on the surface of the satellite is invariable, the effective optimization is:

1、选择效率更高的太阳能电池板材料；

1. Select solar panel materials with higher efficiency;

2、充分利用半影时间，进一步研究可以在半影区提供电力的太阳能电池板；

2. Make full use of the penumbra time to further study the solar panels that can provide power in the penumbra area;

3、在对掩星次数没有影响的情况下，增加 CubeSat 卫星的轨道高度，可以卫星日照区时间，但本质上轨道高度是被第一节所约束，所以不属于本节优化。

3. If the number of occultations is not affected, the orbit height of CubeSat satellite can be increased to increase the time of the sunshine zone of the

satellite, but in essence, the orbit height is constrained by the first section, so it does not belong to the optimization of this section.

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五、 光照度分析
V. Illumination Analysis

5.1 成像设计说明
Imaging Design Description

5.1.1 靶面照度计算公式
Calculation formula of target surface illuminance

靶面照度计算公式：
Calculation formula of target surface illuminance:

$$E = \frac{E_0\rho}{4}\tau_1\tau_2\left(\frac{1}{F}\right)^2\cos^4\beta$$

其中：E——靶面照度　　E_0——景物亮度
Where: E — — Illuminance of target surface E0 — — scene brightness

τ_1——大气透过率　　τ_2——光学系统透过率
τ_1-Atmospheric Transmittance τ_2— — Transmittance of optical system

β——像面边缘视场角　　ρ——地面反射率
β— — Field angle of image plane edge　ρ-Ground reflectivity

F——光学相对孔径
F — — Optical relative aperture

太阳位置 Sun position	太阳高度（度） Solar altitude (degrees)	时间 Time	亮度 Brightness
地平线以上 Above the horizon	70	白天 Day	102000
	60		90000
	50		76000
	40		58000
	30		39000
	20		23000
	15		15000
	10		9000
	5		4000
地平线以下 Below the ho	0	黄昏 Dusk （黎明） (Dawn)	700
	1		500
	2		200
	3		96
	4		33
	5		12
	6		3.5

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表 6 地表亮度表（单位 lux/sr）
Table 6 Surface Brightness (Lux/sr)

物体材质 Object material	反射率 Reflectivity	物体材质 Object material	反射率 Reflectivity
沥青 Asphalt	5 ~ 10%	混凝土（干） Concrete (dry)	17 ~ 27%
深色土壤 Dark soil	5 ~ 15%	干草地 Hay field	20 ~ 30%
天然水 Natural water	6 ~ 10%	浅色/沙性土壤 Light-colored/sandy soil	25 ~ 45%
阔叶林 Broad-leaved forest	15 ~ 20%	污浊的雪 Dirty snow	40 ~ 50%
草地 Grassland	15 ~ 25%	干结新雪 Dry and fresh snow	80 ~ 95%

表 7 地面不同物体的反射率(在计算时取 30%)
Table 7 Reflectivity of different objects on the ground (30% in calculation)

工作距离 Working distance	1km	3km	5km	10km	>80km
大气透过率 Atmospheric transmittance	0.67	0.52	0.35	0.11	0.05

表 8 大气透过率（可见光）
Table 8 Atmospheric transmittance (visible light)

5.1.2 信噪比计算公式 Signal-to-noise ratio calculation formula

$$\frac{S}{N} = 20\,lg\left(\frac{E\zeta\Delta t}{Ke_n}\right)$$

其中：E ——靶面照度　　ζ——成像灵敏度　　Δt —— 曝光/ 积分时间
Where: E — target surface illumination — imaging sensitivity — exposure/integration time

K ——转换增益　　　　e_n——噪声
K — — conversion gain En-Noise

高度 Height km	地面亮度lux/sr Ground luminance Lux/sr	地面反射率 Ground Reflectivity	大气透过率 Atmosphere Transmittance	镜头透过率 Camera Lens Transmittance	边缘视场角° Edge Angle of view °	光圈 Aperture F	靶面照度 Target surface illumination lux	成像灵敏度 Imaging sensitivity mv/lux.ms	转换增益 Conversion gain uv/e	噪声 Noise e	积分时间 Integration time ms	信噪比 Signal to noise ratio dB
10	3000	0.3	0.11	0.8	0.95	2.0	4.9473	3.50	49.1	23.30	0.66	20

表 9 靶面照度测算对应可以成像最短积分时间表
Table 9 Shortest integration schedule of target surface illuminance calculation corresponding to imaging

5.2 成像分析任务 Imaging analysis task

任务轨道： 四组太阳同步轨道， 降交点地方时分别为 6:00 am/7:00 am/8:00am/9:00 am；给定积分时间：1ms；相机其他参数如表 10 所示；分析一年内可成像（即信噪比>20dB）的总时长。

Mission orbit: four sets of sun-synchronous orbits, with local time of descending node at 6:00 am/7:00 am/8: 00am/9:00 am; Given integration time: 1ms; Other parameters of the camera are shown in Table 10; The total time available for imaging (i.e., signal-to-noise ratio > 20 dB) in a year was analyzed.

由于可成像要求信噪比>20dB，即得 E>3.2687，而 E 的表达式为，
Since the imaging requires a signal-to-noise ratio > 20dB, E > 3.2687 is obtained, and the expression of E is,

$$E = \frac{E_0\rho}{4}\tau_1\tau_2\left(\frac{1}{F}\right)^2\cos\beta = \frac{E_0 \times 0.3}{4} \times 0.05 \times 0.8 \times \left(\frac{1}{2}\right)^2 \cos(0.95°)$$

得$E_0 > 4361$。
$_0> 4361$.

由地表亮度表三次样条插值，可得星下点太阳高度（度）需满足的条件为：

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According to the cubic spline interpolation of the surface brightness table, the conditions that the solar altitude (degree) of the substellar point needs to meet are as follows:

$$angle \geq = 5.380160279090210°$$

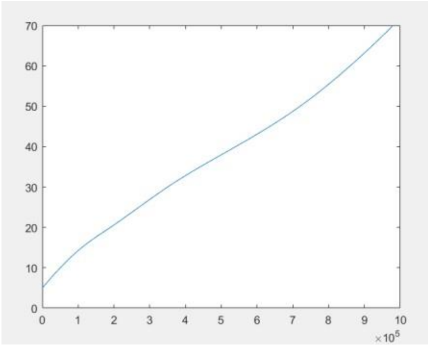

图 15 高度角亮度插值

Figure 15 Elevation angle luminance interpolation

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由于STK直接求解卫星太阳高度角比较方便，对于近地轨道卫星而言，任意时刻的太阳高度角和星下点的太阳高度角有如下关系：

Since it is convenient for STK to directly solve the solar altitude angle of the satellite, for the low-earth-orbit satellite, the solar altitude angle at any time and the solar elevation angle at the sub-satellite point have the following relationship:

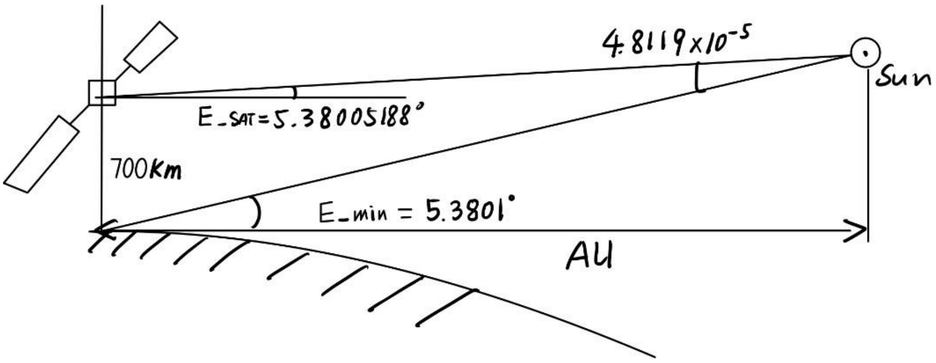

图 16 卫星太阳高度角与星下点太阳高度角的关系

Fig. 16 Relationship between satellite solar altitude and subsatellite solar altitude

可以看出由于天文单位相较于地球半径和轨道半长轴过于大，两者高度角几乎没有差别，故可以认为卫星太阳高度角近似代表了星下点的太阳高度角。

It can be seen that because the astronomical unit is too large compared with the radius of the earth and the semi-major axis of the orbit, there is almost no difference between the two altitude angles, so it can be considered that the satellite solar altitude angle approximately represents the solar altitude angle of the substellar point.

即$elevation\ angle \geq= 5.380015188°$

即 $\geq= 5.380015188°$

现在设计四条降交点地方时分别为6:00 am/7:00 am/8:00am/9:00 am的SSO

Now design four SSO at 6:00 am/7:00 am/8: 00am/9:00 am respectively

卫星。

Satellite.

本文选取ODIN卫星作为参考，修改其TLE数据中的升交点赤经，使其满足要求，分别是：

In this paper, the ODIN satellite is selected as a reference, and the right ascension of the ascending node in its TLE data is modified to meet the requirements, respectively:

ODIN_0600
1 26702U 01007A 22006.62971913 .00000587 00000-0 41159-4 0 9997 2 26702 97.5290 17.8534 0011907 120.2646 239.9762 15.08923838141865
ODIN_0700
1 26702U 01007A 22006.62971913 .00000587 00000-0 41159-4 0 9997 2 26702 97.5290 32.8534 0011907 120.2646 239.9762 15.08923838141865
ODIN_0800
1 26704U 01007A 22006.62971913 .00000587 00000-0 41159-4 0 9997 2 26702 97.5290 47.8534 0011907 120.2646 239.9762 15.08923838141865
ODIN_0900
1 26705U 01007A 22006.62971913 .00000587 00000-0 41159-4 0 9997 2 26702 97.5290 62.8534 0011907 120.2646 239.9762 15.08923838141865

表10 SSO 的TLE

Table 10 TLE for SSO

得到如下结果：

The results are as follows:

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降交点地方时 Local time of descending node	0600AM	0700AM	0800AM	0900AM
成像时间（d）Imaging time (d)	116.6986	151.9479167	162.7753472	167.421875

表 11 不同降交点地方时对于成像时间

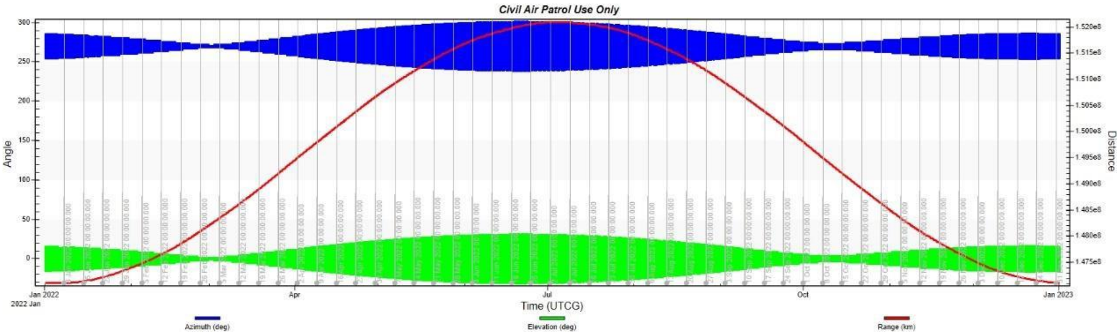

Table 11 Local Time of Different Descending Nodes to Imaging Time

图 17 降交点地方时 0600 的太阳倾角变化

Fig. 17 Variation of solar inclination at 0600 local time of descending node

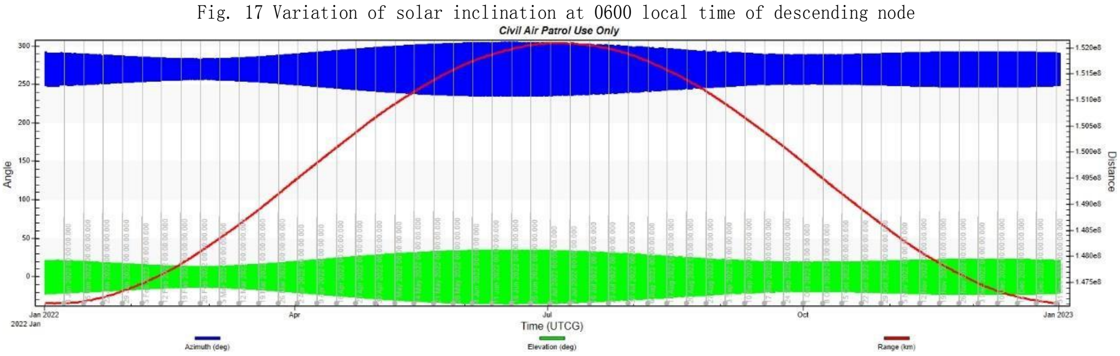

图 18 降交点地方时 0700 的太阳倾角变化

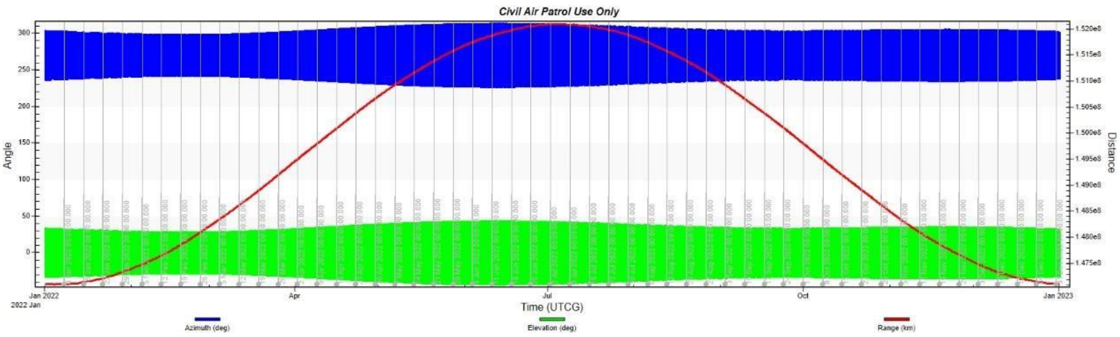

Fig. 18 Variation of solar inclination at 0700 local time of descending node

图 19 降交点地方时 0800 的太阳倾角变化

Fig. 19 Variation of solar inclination at 0800 local time of descending node

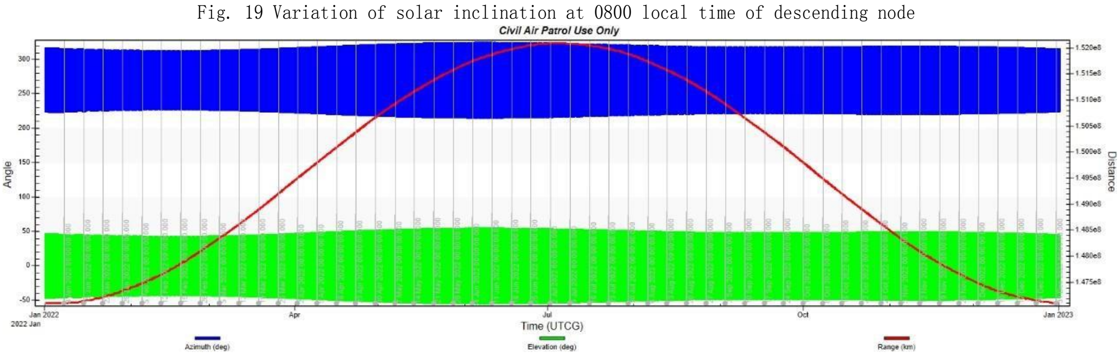

图 20 降交点地方时 0900 的太阳倾角变化

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Fig. 20 Variation of solar inclination at 0900 local time of descending node

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