SatComSim: a Toolkit for Analysis and Optimization of the field of view of Communications Payload in Space-Ground Communication

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Abstract—For high-precision millimeter wave communication tasks, the communication field of view being occluded will seriously affect its communication quality. Accurate analysis of the field of view of the communications payload in space-ground communication, which is occluded by the solar panels and other payloads outside the satellite capsule, is the basis for optimizing the communications payload layout. In order to effectively analyze the occlusion of the communication field of view, this paper proposes a satellite communication field of view calculation simulator - SatComSim, which is based on Pro/E and STK software to obtain the basic data and calculate the occluded communication field of view through collision algorithm to provide important reference analysis results for subsequent research. Finally, we simulate the occlusion of the field of view under different layouts of payloads outside the satellite capsule and field of view ranges based on SatComSim, and optimize the communications payload layout and field of view. The simulation results show the effectiveness of SatComSim in the communications payload field of view analysis, which has an important role in optimizing the communications payload layout and improving the utilization of communication resources.

1. INTRODUCTION
With the booming development of satellite communication technology and its application areas, high-precision space-ground communication has played a key role in navigation, military, space and other fields. Millimeter wave has the advantages of wide frequency band and high transmission rate, and has become the focus of current research[1, 2]. However, millimeter wave diffraction capability is poor and penetration loss is serious, especially for high-precision communication tasks. The presence of obstacles in the communication field of view will cause interference, power loss, etc., affecting the communication accuracy. In order to ensure the quality of space-ground communication and optimize the layout of payloads outside the satellite capsule, the communication payload field of view analysis becomes an important part of the overall design of the satellite.

Determining the presence of occlusion in the field of view of the communication payload is a typical collision detection problem. The purpose of collision detection is to detect whether a collision, that is, contact or penetration, has occurred between two or more objects in a virtual space. Collision detection
needs to take into account not only the geometric models of the objects, but also their relative positions to each other. Therefore, to analyze the effect of the field of view of the communications payload being occluded by solar panels and other payloads during the space-ground communication, it is necessary to consider the position and attitude of the satellite, the geometric models of the solar panels and the other payloads outside the satellite capsule and their layout.

Specialized software has been developed in the areas of satellite attitude analysis, payload geometry modelling and mathematical analysis and computation, but the systems are relatively independent of each other. In order to analyze the communication field of view, it is not only necessary to optimize the upper layer collision algorithm, but also to realize the dynamic interaction between multiple software, which undoubtedly increases the difficulty of communication field of view analysis. As the study of satellite millimeter wave communications intensifies and the urgent need for high-precision communication, there is an increasing need for designers to refer to the effect of the communication field of view being occluded during the overall design of the satellite phase. But there is currently a lack of professional satellite communications field of view simulation platforms to help designers perform fast and accurate analysis.

Therefore, this paper proposes a simulation tool for analyzing the occluded field of view of satellite communication, SatComSim, which can simulate the motion attitude of satellites and solar panels, and analyze the occluded field of communications payload quickly and accurately based on the geometric model of solar panels and other payloads outside the satellite capsule. Finally, this paper takes the payloads layout outside a satellite capsule as an example, based on SatComSim, it simulates the occlusion of the field of view under different layouts and field of view, and calculates the optimal communication field of view range and communications payload installation position.

This paper is structured as follows: Chapter 2 introduces the current work on satellite field of view load analysis and communication field of view occlusion algorithm, Chapter 3 introduces the architecture and logical units of SatComSim, Chapter 4 optimizes the field of view range and layout of a satellite communications payload based on SatComSim, Chapter 5 summarizes this paper.

2. RELATED WORK

2.1 Satellite Payload Field of View Analysis
At present, the research on the analysis of the satellite payload field of view is mainly focused on the optical sensor (star sensor). Although the analysis object is different from the communications payload, the essence of the problem is the analysis of the occluded field of view, so it is of some reference significance. He Heng designed the field of view occlusion analysis tool of optical sensor. The tool is based on the three-dimensional CAD software SolidWorks, using the SolidWorks API functions and Visual Basic programming language for secondary development, and realized the field of view occlusion calculation of the optical sensors[3] . Zhang Hui used STK to simulate the field of view of the star sensor, and gave information such as the time period and duration of stray light in the field of view caused by occlusion [4]. Liao Ying used STK to interact with the Matlab for dynamic data exchange, established a star sensor field of view analysis model, and completed visual simulation of occlusion[5]. Xiao Hongguang and others based on the ray tracing method and hierarchical bounding volume algorithm to simulate and analyze the field of view of the star sensor [6]. At present, the analysis of the satellite payload field of view does not take into account the impact of the geometric model of the occlusion object and the attitude of the satellite at the same time, which leads to the fact that the simulation environment cannot fully match the actual situation of the satellite operation, which affects the accuracy of the simulation results.

2.2 Collision Detection Algorithm
The communications payload field of view being occluded by the solar panels and the other payloads can be converted to detect whether the field of view collides with the geometric models of solar panels and the other payloads. Collision detection algorithms are mainly divided into three categories:
geometric method, space division technology and hierarchical bounding volume technology. The geometric method mainly analyzes the geometric structure of the model, and determines whether a collision occurs by tracking the closest features (points, edges, and surfaces) between the models. Typical geometric method are Lin-Canny and Enhanced GJK algorithm \[7, 8\]. Space division technology divides the entire virtual space into small cells of equal volume, assigns objects to one or more cells, and then performs collision detection on all objects occupying the same cell. Commonly used algorithms include uniform networks, octrees and BSP trees\[9, 10\]. Hierarchical bounding volume technology is the current mainstream collision detection algorithm. This method is mainly to organize objects in a hierarchical manner to quickly exclude disjoint objects. There are mainly ball bounding volume trees, AABB hierarchical trees, OBB hierarchical trees, etc.\[11-13\]. This paper is mainly based on the hierarchical bounding volume technology to detect the occlusion of the communication field of view.

3. SATCOMSIM SYSTEM ARCHITECTURE

3.1 System Design

The analysis of occluded communications payload field of view requires consideration of the position attitude of the satellites and solar panels, geometric models of solar panels and other payloads outside the satellite capsule, and the process of implementing the occlusion algorithm of the communication field of view. SatComSim builds the simulation system framework based on these elements. The framework is shown in Fig. 1, divided into three layers: data source layer, cleaning layer and computing layer. By entering the orbital parameters of the satellite, the time of operation of the satellite, the position of the ground station, the range of the communication field of view, the geometric models of the solar panels and the payloads outside the capsule and their layout, the user can obtain the periods of time during which the satellite can communicate with the ground station, and the occluded communication field for each period of time.

![Figure 1. SatComSim framework](image)

3.2 Data Source Layer

The data source layer is the foundation of SatComSim and provides the complete data set for the simulation framework. This layer is to generate the position attitude information of the satellite and the sun, and the communicable time period between the satellite and the ground station based on STK; to build the geometric models of the solar panels and other payloads outside the capsule based on Pro/E, and to realize the dynamic interaction between STK, Pro/E and the cleaning layer.

Pro/E is an excellent CAD 3D software. The user builds the geometric models of the solar panels and payloads outside the capsule in Pro/E. SatComSim then imports the geometric models from Pro/E into the cleaning layer based on the STL format file. The STL format specifies that the model is described as a triangular patch with three vertices and a surface with multiple patches. The information for each patch consists of the surface normal vector and the vertex coordinates that satisfying the right-hand coordinate system. The STL file information allows for the reproduction of the geometric components of the model in the cleaning layer for the next step of analysis.
SatComSim generates the position attitude data of the satellite and the Sun based on STK, as well as the time period during which the satellite can communicate with the ground, using parameters such as the satellite's orbit entered by the user. STK provides connectivity modules to help users analyze the data. SatComSim transfers data to the cleaning layer based on STK’s aeroToolbox and mexConnect connection module.

### 3.3 Cleaning Layer
The cleaning layer connects the data source layer to the computing layer and is responsible for data clipping and pre-processing. Since we are only concerned with the occluded communication field of view when the satellite can communicate with the ground station. Thus, the cleaning layer extracts the position attitude information of the satellite and the Sun, when the satellite communicates with the ground station. And the cleaning layer calculates the attitude of the solar panels based on the position information of the sun. To reduce the algorithmic complexity of the computing layer, this layer establishes the satellite coordinate system and the solar panels coordinate system, and computes the conversion matrix between them and the ECI (Earth-Centered Inertial Coordinate System) to provide the converted data for the computing layer.

![Figure 2. Solar Panels Coordinate System, Satellite Coordinate System and ECI Coordinate System.](image)

We establish the satellite coordinate system based on the three-axis stable attitude of the satellite. Due to the requirement of communication with the ground, it is assumed that the direction of the satellite's bottom points to the center of the earth. Thus the satellite coordinate system OA was established as shown in Fig. 2, where the $X_s$ axis is the direction of the satellite's running speed, the $Z_s$ axis is always pointing to the center of the earth, and the $Y_s$ axis is always perpendicular to the $O_sX_sZ_s$ plane.

The solar panels always maintain a direction perpendicular to the incident solar ray. The center of the solar panels is collinear with $Y_s$ axis. The solar panels coordinate system $O_s$ is established, the $X_s$ axis is the opposite direction of the solar ray vector, the $Z_s$ axis is perpendicular to the $Y_s$ axis, and is a rotating axis of the solar panels. Solar panels are perpendicular to the solar ray by rotating about $Z_s$ axis and $Y_s$ axis. The conversion matrix between coordinate systems can be easily calculated based on the position and attitude data of the satellite and the Sun[14].

### 3.4 Computing Layer
The computing layer is the top layer of SatComSim, which implements the communication field of view analysis algorithm based on the AABB hierarchical bounding volume technology to analyze the communication field of view occluded by solar panels and other payloads outside the capsule. To reduce ineffective partitioning, SatComSim uses a dynamic division strategy to adjust the division state in time.

1) **Hierarchical bounding volume technology**
The basic idea of a bounding volume is to replace a complex geometric object with a slightly larger geometric object with simple properties, the AABB bounding volume is defined as the smallest hexahedron containing the object parallel to the coordinate axis. The AABB bounding volume is simple in construction, small in computation, and does not require much storage space. But it is not compact, especially for irregular geometries, the redundant space is large, and when the object is rotated, it cannot be rotated accordingly. In order to solve the problem of compactness, we use space division technology to divide the space inside the volume into regular cells according to the tree structure, that is, to form a hierarchical bounding volume. The process of collision detection is the process of determining whether there are intersections between tree nodes. In the cleaning layer, the satellite coordinate system and the solar panels coordinate system and the conversion equation between them are established, which ensures that the payloads and solar panels are fixed in the corresponding coordinate system, and only the motion state of the coordinate system needs to be considered, thus solving the problem that the AABB cell cannot rotate with the object.

A hierarchical division tree needs to be established during the in-box space division phase. Generally, the divided tree structure selected is a binary tree, a quadtree, and an octree. To the octree, for example, the octree represents objects as a combination of AABB cells of equal volume. When a cell (the length of three sides is \(x_k, y_k, z_k\)) detects a collision, it will be divided into eight sub-cubes at \(x_k/2, y_k/2, z_k/2\). The binary tree and the quadtree are similarly divided at the midpoint of one edge and two edges respectively.

2) Dynamic division strategy

The larger the degree of the tree is, the smaller the depth of division is. In order to increase the efficiency of the algorithm, it is necessary to minimize the size of the leaf node so that it contains as few objects as possible while minimizing the depth of the tree. With this in mind, the octree is a well-divided structure. However, the octree division structure, although simple and convenient, is more suitable for rectangles with closer length and width and height, and for some rectangles with a large difference in length and width and height, it is easy to divide out narrow or flat sub-cells, resulting in reduced algorithm efficiency. Therefore, SatComSim adopts the dynamic division strategy, which is to dynamically adjust the number of divided cells according to the current cell shape.

We define flat cells and narrow cells as: the longest side of the cell for \(maxlen\), the remaining two sides for \(\alpha, \beta\), when (1) conditions are met, the cell is a narrow cell; when (2) conditions are met, the cell is a flat cell.

\[
\begin{align*}
maxlen & \geq k\alpha \\
maxlen & \geq k\beta \\
k & > 1
\end{align*}
\]  
(1)

\[
\begin{align*}
maxlen & \geq k\alpha \\
maxlen & < k\beta \\
k & > 1
\end{align*}
\]  
(2)

The dynamic division strategy can then be expressed as:

a) Determine the appropriate \(k\) based on the collision detection object.
b) Determine which of the following cell types the current cell belongs to, and then split it according to the corresponding entry.
   i. Narrow cells, divided at the midpoint of the longest side, forming a binary tree.
   ii. Flat cells, divided at the midpoint of the longest and second longest sides, forming a quadtree.
   iii. In other cases, forming an octree.

It can be found that too large \(k\) will degenerate the dynamic division strategy into an octree structure, and too small \(k\) will degrade the dynamic division strategy into a binary tree structure. The choice of \(k\) value needs to be selected according to the specific application, generally set to 2 or 3.
4. Optimization of the Communications Payload Based on SatComSim

In order to assess the effectiveness and flexibility of SatComSim in the field of view analysis of the communications payload, this chapter takes a LEO orbiting satellite and the high-precision communication mission requirements of that satellite as an example, based on SatComSim to analyze of the occlusion of field of view that can affect the accuracy of the communication mission, that is, the occlusion rate of solar panels and the other payloads outside the capsule to the communication field of view is greater than 15%. And re-optimizes the field of view range and layout of the communication payload based on the analysis results.

4.1 Simulation Parameters

The outer layout of the LEO orbiting satellite capsule is shown in Fig. 3, and its communication ground station is Beijing Station. The communication field of view may be occluded by solar panels and payload L. The installation range of the communications payload is the outer space of the satellite capsule. Since both the communications payload and payload L need to be grounded, the installation range of the communications payload can be simplified to the Y axis of the satellite coordinate system. The payload L and the solar panels are fixed in position, and each occupy one end of the installable range.

![Figure 3. The outer layout of the LEO orbiting satellite capsule](image)

The larger the field of view is, the greater the chance of passing the station is, which means the greater the duration of passing the station is. But too large a field of view is more susceptible to interference and can result in unreliable communications due to too small a ground elevation angle. Based on empirical values, the range of field of view considered in this paper is 50° to 70°.

This chapter selects the optimal communications payload installation location and field of view range with the goal of minimizing the cumulative duration of the communication field of view occlusion rate greater than 15% during one year of communication between the satellite and the ground station.

4.2 Simulation Results

Under different installation positions and field of view, the simulation results of the communication field of view occluded by solar panels and payload L are shown in the Fig. 4. It can be seen that the larger the field of view range is, the longer the cumulative time of the field of view being occluded is. But as shown in Fig. 5, when the field of view range is larger, the cumulative communication time will be longer. So that the optimal field of view is 70° under comprehensive consideration.

The optimal installation location for the communications payload is 7 meters from the solar panels, when the cumulative length of time the communication field of view being occluded is minimal. Further analysis of the occluded field of view, when the distance between the communications payload and the solar panels is less than 7 meters, the solar panels have a greater effect on the field of view. So the greater the distance between the communication payload and the solar panels is, the less the
occluded field of view is. However, when it exceeds 7 meters, the communication payload is more affected by the payload L. Since the occlusion effect from payload L is fixed, when payload L is too close to the communications payload, the occlusion rate of payload L is more than 15%, which will affect the communication accuracy throughout the communication time.

![Figure 4. Cumulative length of time of communication field of view affected by occlusion](image)

![Figure 5. Cumulative length of time of satellite-to-ground station communication](image)

5. CONCLUSION

This paper is devoted to analyzing the effects of solar panels and other payloads outside the satellite capsule on the obstruction of the communication field of view in a high-precision millimeter wave communication scene. In this paper, a satellite communication field of view calculation simulator, SatComSim, is proposed, which is based on Pro/E and STK to generate basic data and uses a hierarchical bounding volume algorithm based on a dynamic division strategy to calculate the occlusion communication field of view. By enabling dynamic interaction between the underlying software, the tool effectively utilizes the advantages of Pro/E and STK, greatly simplifying the difficulty for developers to analyze the occluded communication field of view while ensuring accuracy of results. Finally, based on SatComSim, we simulate the satellite's communication field of view under different field of view and layout, and obtain the optimal installation location and field of view of the communications payload. Simulation results show that SatComSim can reliably analyze the occlusion of the communication field of view, which has an important role in optimizing the design layout of communication payload and improving the utilization of communication resources.

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