**The Hong Kong Polytechnic University Department of Computing**

COMP4913 Capstone Project

Final Report

**Simulation and Analysis of Inter-satellite**

**Communication for Real-Time Data**

**Downloading**

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# Introduction

## Motivation

Nowadays, thousands of satellites are launched in the Low Earth Orbit (LEO). LEO satellites orbit below 2000 kilometers above the earth. It is expected that in the period from 2014 to 2023 an average of 115 small LEO satellites will be launched per year (Sebestyen et al., 2018). Which is used for communications, military reconnaissance, spying and other imaging applications. The LEO satellites made for communication benefit from the lower signal propagation delay in LEO. The environment in LEO provides lower propagation delay and able to communicate with Earth-based stations with utmost efficiency (Shustova, 2022), resulting in low-latency, high bandwidth, and universal internet connectivity (Vasisht et al., 2021). Meanwhile, LEO satellites are closer to the earth's surface, so imaging satellites will also be able to capture better and more detailed pictures (Shustova, 2022).

However, the communication range of LEO satellite exist a coverage issues, and there is a limited numbers of ground station. It results to an LEO satellite may fly for many hours to end up in the communication scope of a ground station and takes a long time for an LEO satellite to download the data to the ground.

## Background and Problem Statement

The communication coverage of Low Earth Orbit (LEO) satellites is much smaller than the higher altitude satellites. Ground stations can communicate with LEO satellites only when the satellite is in their visibility region and the duration of the visibility, and the communication vary for each LEO satellite passing over the station since LEO satellites move too fast over the Earth. (Cakaj et al., 2014). As a result, an LEO satellite may fly for many hours to end up in the communication scope of a ground station. Since the number of ground stations on the ground is limited, it takes a long time for an LEO satellite to download the data to the ground. The data satellite must wait at the satellite before it comes in contact with a ground station (Vasisht et al., 2021).

Therefore, inter-satellite communication is hard to meet the strong real-time constraints. A real-time system requires to guarantee events can be completed in a set amount of time. However, cause of the feature of LEO satellites and the distribution is not fixed, it is hard to complete the data transmission in a set amount of time when the path of data transmission is not ensured.

Inter-satellite communication offers a new opportunity to achieve real-time data downloading, even if the number of ground stations is limited. Suppose an LEO satellite has some data to download and cannot find a ground station within a specified deadline. In that case, the satellite can transfer the data to another satellite that can communicate to some ground station. Therefore, the data downloading may probably meet the specified deadline.

In this project, we study the problem of meeting real-time data downloading requirements with inter-satellite communication. When a satellite has data to download, it can either communicate to a ground station (if the satellite is in the communication scope of the ground station) or transfer the data first to another satellite that can communicate to some ground station. We will simulate the communication between an LEO satellite and a ground station and multiple satellites, specifically the communication capability and its delay. As an LEO satellite may have multiple choices in the downloading data path, we will explore if there is at least one path that can meet the download deadline, based on the simulation.

## Aim and Objectives

The overall objective is to analyze if the data download deadline can be met given the data on an LEO satellite can be transferred either directly to a ground station or via some other LEO satellite, given a configuration of an LEO satellite constellation and a set of ground stations. The analysis is conducted based on the simulation of the communication behavior between LEO satellites and between an LEO satellite and the ground stations.

There are several sub-tasks to achieve the above objective:

1. Simulation: to simulate the communication behavior
   1. To simulate the position of each satellite in space at a given time, based on which we can evaluate whether two satellites can communicate.
   2. To simulate whether a satellite is in the communication scope of a given ground station, given the related parameters.
   3. To simulate the data transfer latency, either between satellites or between a satellite and a ground station.
2. Optimization

There can be multiple paths for a satellite to download the data to the ground. Based on the simulation capability, an optimization algorithm will be developed to find the shortest communication path and check if the communication along this path can meet the data download deadline.

The simulator simulates the communication between Low Earth Orbit (LEO) satellites and the ground station, including the communications between LEO satellites. It aims to compute the real-time capabilities of a group of LEO satellites in data downloading by simulating the environment of LEO and referring the existing satellites to obtain data close to reality. Meanwhile, the simulator simulates the LEO environment with space geometry and satellite communication.

The simulator will simulate the real LEO environment by using the real LEO environment feature and the space geometry when calculating the satellite orbit. The LEO satellite visibility modelling and decisions of data transmission will use the existing satellite data to guarantee the result is close to reality.

The outcome of the project will be a simulator to show all the orbits, data transmission path, and transmission delay. The final outcome will allow users to customize the orbit and satellites including the orbit used in the simulation, find out the path of data transmission and show the delay of the transmission.

# Project Design and Methodology

The Project Simulation consists of the visibility Model, Communication Delay Model, and Path Decision Model. Their relationship is shown in Fig. 1.

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Fig. 1 Flowchart of all Component

## LEO Satellite Space Geometry Modeling

In the space geometry modeling, there are mostly using the mathematical algorithm in space geometry. These algorithms will be development with python and using the “NumPy” library to assistance.

To local the ground target and Satellite in space, the Earth-Centered Inertial (ECI) is used as the coordinate system. ECI coordinate system is a 3-dimensional Cartesian coordinate system with the original fixed center in the Earth's mass center, which remains fixed with respect to Earth's surface in its rotation and rotates with respect to stars.

Except for using the (x, y, z) to represent the point in the coordinate system, right ascension (denoted by α) and declination (denoted by δ) are used to represent the angular position of the point. The right ascension of point P in Fig. 2 is the angular distance of point P which is measured eastward along the celestial equator from the x-axis of an ECI coordinate to point P. The declination is the angular distance from the equatorial plane to point P in Fig. 2 which is measured along the hour circle passing through point P.

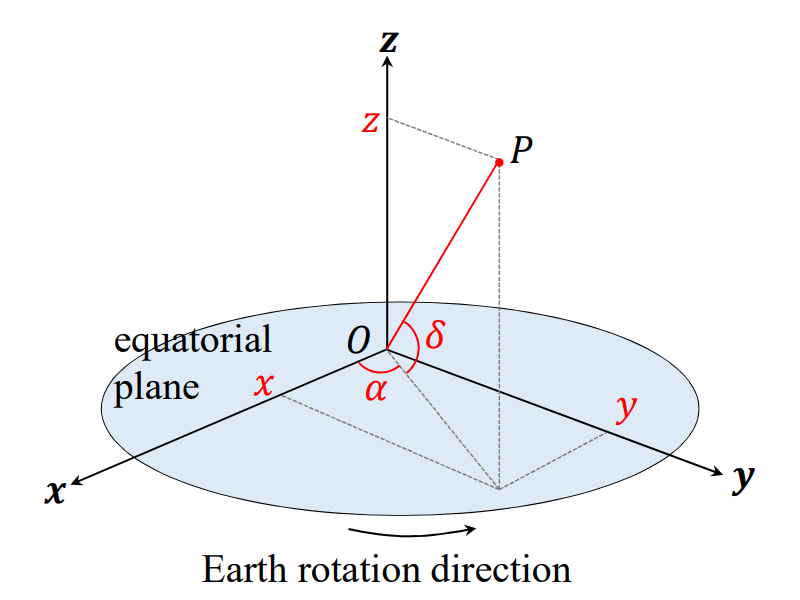


Fig. 2 Elements of ECI coordinate system

Fig. 2 shows the ECI coordinate and the position parameters of point P. r in Fig. 2 is the distance from point P to the original point in the ECI coordinate system. The (x, y, z) value in the coordinate system can be computed by the equations below.

Earth is an ellipsoid very close to a perfect sphere. But for simplicity of the calculation, the Earth is assumed as a perfect sphere. The self-rotation of the Earth is eastward along the celestial equator with an angular speed of 2π per day. Because of the self-rotation of the Earth, the (x, y, z) value in the coordinate system and the right ascension of the point following the self-rotation and satellite movement continue to change in the ECI coordinate. But the latitude of the point, coinciding with its declination, remains unchanged.

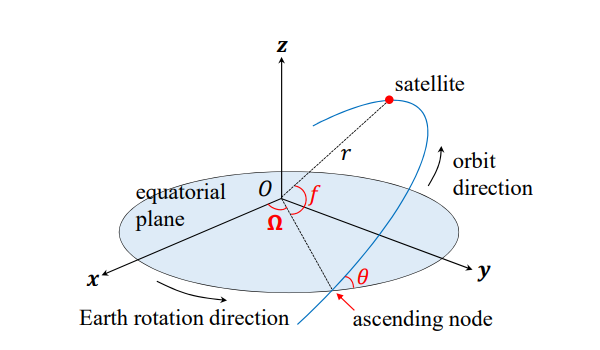


Fig. 3 Elements of Satellite Orbit

In Fig. 3, point P has a longitude (λ) and a latitude (φ). At time , P has a right ascension of and a declination of . After a time passed, a new right ascension , new declination cam be computed by the following equations. Where denotes the angular speed of self-rotation of the Earth ( = 2π/day).

Because of the altitude of LEO satellite is low which take the orbit is close to the perfect circle. Therefore, in this project, satellite orbit is assumed as a circular orbit. There is orbit information shown in Fig. 3 used to describe a satellite as below.

* R: the radius of the orbit
* θ: the inclination angle from the equatorial plane to the orbit plane which measured above the equatorial plane when θ in , the orbit is same direction as the Earth rotation. when θ in , the orbit is opposite direction as the Earth rotation
* Ω: the right ascension of the ascending node which is the point where the orbit crosses the equatorial plane northward.
* F: the true anomaly which is the angular difference from the equatorial plane to the initial position of the satellite.

## LEO Satellite Visibility Modeling

### Visibility Modeling for Observation

To model the characteristics of the visibility scope of the satellite for the observation target, the visibility scope is determined by the altitude of the satellite and the capability of the satellite camera. As Fig. 4, S is the satellite, P is the observation target, and O is the center of Earth. There is a sub-satellite point B which is a point on Earth's surface intersecting with the line O to S. γ is the plane that is tangent to the Earth at P.

The camera of the satellite is mounted on a head and initially points to the sub-satellite point. At the run time, the camera can swing for an off-nadir angle (β in the Fig. 4) to take an image. The off-nadir angle is limited, so the visibility scope of an LEO satellite is limited by the maximum off-nadir angle. If the satellite is right above the observation point P, the off-nadir angle will be 0.

The current β can be computed with the observation target and the satellite. If the current is smaller than the maximum β and the satellite is above the γ plane, then the satellite can capture the image of the observation target.

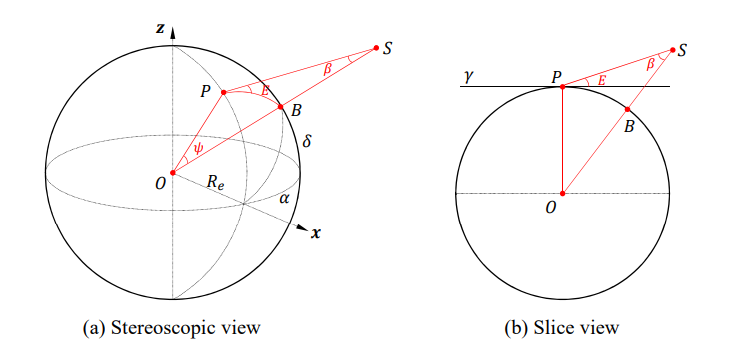


Fig. 4 Observation Visibility

Because the position of the observation target and satellite is continuously changed by the Earth's rotation and satellite movement. For future development of communication, the visibility model can compute the time window of the satellite's ability to visit the observation target by comparing the β at any time with the maximum β.

### Visib**ility Modeling for** Satellite to Ground Station Communication

To communicate with the ground station, the satellite must be within the communication scope of the ground station. The visibility model is used to find out if the ground station is visitable by a satellite. The main determining factor of the modelling is the elevation of the ground station (as shown by angle E in Fig. 4) which is the angle to measure the perpendicular to the earth’s surface. if the elevation angle of the ground station is 90 degrees, it means the satellite is right above the ground station. The elevation angle can be changed by the Earth's rotation and satellite movement. When the elevation angle is too small, the satellite will not able to communicate with the ground station.

Because the visibility model of communication is similar to the visibility model of observation, the visibility model of observation can be reused to compute the communication scope. P in Fig. 4 can seem like the ground station. According to the principles of triangles, there is a fixed relationship between the angle β and elevation E, so

The minimal elevation is typically specified by the ground station. In the range [0◦, 90◦] when E increases, β decreases. So, the maximal β can be computed by the above equation. When current β is smaller than the maximal β, the satellite is within the communication scope. And able to compute the time window of the satellite's ability to visit the ground station by comparing the β at any time with the maximum β.

### Visibility Modeling for inter-Satellite Communication

If the satellite is not within the communication scope of the ground station, the data can be transferred to another satellite. For this purpose, a visibility model is needed to find out the satellite communication scope. The visibility model in satellite-to-satellite visibility is difference with the satellite to ground station visibility modeling.

Because the distance of satellite-to-satellite communication range is typically unlimited in LEO, so the main determining factor of the model is the communication of two satellites whether being blocked by the Earth. Because the distance of satellite-to-satellite communication range is typically unlimited in LEO, so the main determining factor of the model is the communication of two satellites whether being blocked by the Earth. The maximum off-nadir angle (β in the Fig.5) can be computed by the following equation when S2 is the satellite contain the data.

The current can be computed by the bisector (shown as h in Fig. 5) of and . When is bigger than , both satellites can communicate to each other.

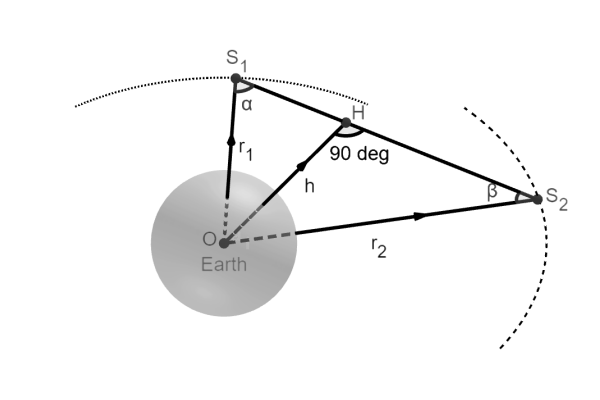


Fig. 5 Satellite to Satellite Visibility

## Communication Delay Model

The Delay of inter-Satellite and Satellite to ground station communication is constructed by transmission delay, propagation delay, buffer delay, process delay.

### Transmission Delay

The transmission delay is the time taken to transmit a single data packet at the data rate of Satellite. Formula as below.

### Propagation Delay

The propagation delay is the time taken for the signal to travel from satellite to satellite or ground station. Most of the Satellite usually use radio, its signal speed is 299,775 km/s. Formula as below.

### Buffer Delay

The buffer delay is caused by cell queuing at each point in the network, which may result from traffic's bursty nature, congestion at the queuing locations (such as earth stations and satellites), or media access control delays.

### Process Delay

Depending on the level of on-board switching and processing, the data packets may experience extra delays () at each satellite hop. In high data rate networks that use packet/cell switching, the switching and processing delays are insignificant when compared to the propagation delays.

### Total Delay

The total delay for a single communication combines the transmission delay, propagation delay, buffer delay, and process delay. Formula as below.

## Path Decision Algorithm

In this section, algorithms are used to compute the distance between satellite and making decision of select the next satellite need to transmit the data. There are three path algorithms is used. They are A\*, Dijkstra, and a self-designed orbit path algorithm. Algorithms is implemented with the “NumPy” and math library to assistance the calculation.

### A\*

The A\* algorithm is a heuristic-based pathfinding and graph traversal algorithm that prioritizes the exploration of nodes based on a combination of the actual distance traveled from the start node and an estimated distance to the goal. The algorithm maintains a priority queue of nodes to explore, selecting the node with the lowest estimated total cost at each step and expanding its neighboring nodes until the goal is reached. In this project, the position of the satellite is time-dependent, and once a satellite is selected as the next node in the path, the communication delay is calculated and updated at the current time. The path cost is defined as the actual distance traveled from the start node, and the estimated distance is the straight-line distance between the current satellite node and the ground station.

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Fig. 6 A\* Algorithm Flowchart

### Orbit path algorithm

The orbit path algorithm is a novel algorithm developed specifically for this project. It is based on the concept of transmitting data from one orbit to another, bringing the data progressively closer to the ground station until it can be transmitted directly to the ground station. Before selecting the next satellite to transfer data, the algorithm will find out which orbit beside is closer to the ground station, then select the satellite in the orbit which is the nearest to the ground station to transfer data. Iteration until the satellite is within the communication scope of the ground station.

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Fig. 7 Orbit path Algorithm Flowchart

### Dijkstra algorithm

The Dijkstra algorithm begins by selecting a source node and evaluating all of its adjacent nodes, determining the distance between the source node and each of them. The algorithm then chooses the node with the shortest distance from the source node as the next node to visit and repeats the process until it reaches the destination node. As each node is visited, its adjacent nodes are added to the priority queue if they have not been visited before, and their distances from the source node are updated if a shorter path is discovered.

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Fig. 8 Dijkstra Algorithm Flowchart

## Experiments and Demonstration

To demonstrate the work of this project, we will use the simulator to output the dynamics of the satellites and the potential communication paths for data downloading, and we will also show the shortest path that is found by the decision-making algorithm.

To setup the parameter, a simple graph interface is developed to setup the parameter of satellite generation and data transmission by using “tkinter” Library. As below.

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Fig. 9 Setting user interface

To demonstration the result, a graph interface is developed to show all the results of each path decision algorithm of the satellite communication and the delay of taditional satellite communication by using the “pyopengl” and “pygame” Library to plot the 3D image of the result as below.

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Fig. 10 Result graph user interface

The details of the results will be stored in an excel file named analysis analysis\_result.xls inside the results folder in the project directory.

# Implementation

## Resources Estimation

### Hardware Requirement Estimation

* Computer able to run .py file

### Software Requirement Estimation

* Python 3.8+
* Pip (for install library)
* Code Editor/ File Editor (VScode/others)

### Use of Library

* numpy, math (For calculation)
* xlwt (For output data to excel file)
* Datetime
* tkinter (For Setting Parameter Interface)
* pygame, pyopengl (For display the final result of path)

## Use of Project

### Setup Parameter

To Setup the parameter of time, position of ground station and observation point. The file in Setting Folder from the project directory can be modify.

Table 1 Setting File

|  |  |  |
| --- | --- | --- |
| **Setting file name** | **Description** | **Format** |
| main\_GROUND\_STATION.txt | contain only one ground station as the point data transfer to | Latitude(degree) Longitude(degree) elevation(degree) |
| main\_OBSERVATION.txt | contain only one observation point as the point to observe | Latitude(degree) Longitude(degree) |
| TIME\_INTERVAL.txt | define the Starting datetime of simulator | yyyy MM dd hh mm ss |

### Prepare the environment

To install all the Library used in the project with the same version, a command should be run in the project directory with following

**pip install -r "requirements.txt"**

### Run the Simulator

To run the simulator, the main.py in the root of the project directory should be executed with the following command.

**python main.py**

Then the simulator will be started.

# Experimental Evaluation

## Evaluation targets

This project aims to simulate LEO satellite communication using a designed simulator. The simulator considers the parameters of the LEO satellites, ground stations, observation points, and data transmission to determine the optimal starting point for data transfer. Using the path decision algorithm described in the design section, the simulator calculates the most efficient path for data transfer to the ground station. The experiments focus on determining the delay of transmit time required, and the performance of each path decision algorithm. Additionally, the experiments compare the path decision algorithm to the traditional method of satellite data transfer.

In the experiment, it intends to answer the following questions:

* The time used in the traditional method of Satellite transfer data
* Comparing different path decision algorithm
* The average time range for each path algorithm to transmit data

## Results and Evaluation

### Traditional Method of Satellite Transfer data

To test the time used in the traditional method of satellite data transfer, the experiment used a satellite that can observe the observation point as the satellite to carry the data. The simulator time was then increased until the satellite was within the communication scope of the ground station, and the communication delay was added to the delay time.

The parameter for the data transfer remained constant, and only the latitude and longitude were varied to determine the time range. The specific parameter values used in the experiment are as follows:

Table 2 Parameter Setting

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| inclination | 97 degree |
| mean motion | 14 revolutions per day |
| Number of orbits | 9 |
| Number of satellites for each orbit | 25 |
| Buffer Delay For Each Satellite | 50 ms |
| Process Delay | 10 ms |
| Package Size | 54 Mb |
| Data Rate | 506 Mb/s |
| Signal Speed | 299792458 m/s (radio speed) |

Using the parameters specified in Table 2, the experiment was conducted within a latitude and longitude range of 0 to 360 degrees, and the following results were obtained:

Table 3 Result of traditional method to transmit data

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Observation Point | | Ground Station | | Transmit Delay (second) |
| Latitude | Longitude | Latitude | Longitude |
| 0 | 0 | 0 | 180 | 3002.357571557039 |
| 270 | 0 | 90 | 180 | 3082.417571526417 |
| 56 | 261 | 304 | 99 | 3070.6275715498405 |
| 0 | 0 | 0 | 30 | 36242.237571588805 |
| 0 | 0 | 0 | 60 | 29586.9475716409 |
| 0 | 0 | 330  (360-30) | 0 | 233.08757151209213 |
| 0 | 0 | 300  (360-60) | 0 | 790.7175715020019 |

Based on the results, the average delay for transmitting data from an earth position to a position opposite on earth is about 3050 seconds. Furthermore, the comparison of transmit delay with latitude or longitude changes indicates that longitude changes have the most significant impact on the delay.

### Average Time range for each path algorithm

In each path decision algorithm experiment, a satellite is chosen as the starting point, which can observe the observation point, and a satellite within the ground station communication scope is selected as the endpoint. The experiment parameters in Table 2 will be used in the experiment.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Observation Point | | Ground Station | | Transmit Delay (second) | | |
| Lat | Long | Lat | Long | A\* | Dijkstra | Orbit Path |
| 0 | 0 | 0 | 180 | 0.7463205217798894 | 0.7449557247804814 | 0.7456292135060938 |
| 270 | 0 | 90 | 180 | 0.7495948969807975 | 0.7498812322163797 | 0.7452856204701312 |
| 56 | 261 | 304 | 99 | 0.7472056694345308 | 0.745441855036228 | 0.9237854453637382 |
| 0 | 0 | 0 | 30 | 0.3476534317411409 | 0.3543720470660122 | 0.3476534317411409 |
| 0 | 0 | 0 | 60 | 0.3642136677274506 | 0.3628650815032996 | 0.5254791354872397 |
| 0 | 0 | 0 | 120 | 0.5562221496146533 | 0.554231819285953 | 1.0998565678105077 |
| 0 | 0 | 330 | 0 | 0.3570286367018671 | 0.3500715515718346 | 0.3564777387550837 |
| 0 | 0 | 300 | 0 | 0.3651893561323917 | 0.3628743653133944 | 0.3651893561323917 |
| 0 | 0 | 270 | 0 | 0.5485485160646866 | 0.546206285341531 | 0.5485485160646866 |

Table 4 result of Each Path Algorithm

According to the result, it finds the average delay range of transmitting data from an earth position to a position opposite on earth is using about 0.765 seconds. For the average time of with Latitude or Longitude changes, it is 0.423 seconds for A\*, 0.421 seconds for Dijkstra, 0.540 seconds for orbit path. Therefore, the Dijkstra algorithm outperforms the others.

The findings from Table 4 indicate that latitude and longitude changes do not abruptly increase transmission delays. Instead, the delays exhibit a linear increase in proportion to the distance between two positions.

# Conclusion

In conclusion, this project aims to analyze the issue of inter-satellite communication systems and simulate them to meet real-time system constraints. The current inter-satellite system cannot ensure the completion of data transmission within a specified timeframe. To address this, the project simulates communication between an LEO satellite, a ground station, and multiple satellites to evaluate communication capability and delay. The objective is to meet the deadline for downloading data from the LEO satellite.

The experiment results indicate that the path decision algorithm is a stable solution that meets the real-time system constraints. In contrast, the traditional LEO satellite data transmission method is prone to significant transition delay time variations due to longitude changes. This method results in unstable transmission delays and is incapable of ensuring data transmission completion within a specific timeframe. However, the path algorithm used in this project provides a stable transmission delay within a second, making it a reliable solution that meets real-time system constraints.

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