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Artículos

Simulation of Access, Coverage, and Orbital Decay for an Optical Micro-Satellite for Colombia*

Simulación del acceso, la cobertura y la decadencia orbital de un microsatélite óptico para Colombia

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Abstract:

The selection of the operational orbit is a critical component for the success of satellite missions, as it must meet specific user requirements, payload constraints, and communication needs. This paper comprehensively analyzes the criteria and parameters used to determine the best orbit for satellite missions, focusing on design variables derived from mission requirements and technical constraints. Several fundamental aspects are evaluated, including coverage of areas of interest, access times to ground stations, revisit times, and satellite lifespan in orbit, through simulations of orbital scenarios. The results show that orbits with inclinations of 16° provide an optimal balance between coverage and revisit times, maximizing operational efficiency over Colombian territory. Satellite constellations are also analyzed, highlighting specific combinations that improve coverage and access times. Furthermore, the analysis of orbital decay and lifespan in orbit confirms that the selected orbits comply with international standards for mitigating collision risk. This article offers a guide for orbit selection in satellite missions, emphasizing a Low-Earth Orbit (LEO) mission, ensuring operational benefits and minimizing risks.
Keywords: Satellite Orbits, Coverage, Revisit Time, Orbit Lifespan, Simulation, Decay, Microsatellite.

Resumen:

La selección de una órbita operacional es un factor crítico para el éxito de las misiones satelitales, ya que debe cumplir con requisitos específicos del usuario, restricciones de carga útil y necesidades de comunicación. Este artículo presenta un análisis exhaustivo de los criterios y parámetros utilizados para determinar la órbita óptima para misiones satelitales, enfocándose en variables de diseño derivadas de los requisitos de la misión y restricciones técnicas. Se evalúan aspectos clave, como la cobertura de áreas de interés, los tiempos de acceso a estaciones terrestres, los tiempos de revisita y la vida útil del satélite en órbita, a través de simulaciones de escenarios orbitales. Los resultados indican que las órbitas con inclinaciones de 16° proporcionan un equilibrio óptimo entre cobertura y tiempos de revisita, maximizando la eficiencia operacional sobre el territorio colombiano. El estudio también examina

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constelaciones de satélites, destacando configuraciones específicas que mejoran la cobertura y los tiempos de acceso. Además, el análisis de la desintegración orbital y la vida útil en órbita confirma que las órbitas seleccionadas cumplen con los estándares internacionales de mitigación de riesgos de colisión. Este artículo sirve como guía para la selección de órbitas en misiones satelitales, con énfasis en misiones en órbitas bajas, asegurando beneficios operacionales y minimizando riesgos.

Palabras clave: órbitas satelitales, cobertura, tiempos de revisita, vida útil en órbita, simulación, decaimiento, microsatélite.

Introduction

The space industry has experienced significant growth in recent decades, driven by the development of advanced technologies and the increasing demand for satellite services. This has encouraged emerging countries to develop their capabilities in the space sector, starting from mission design to in-depth analysis [1]. In this context, orbit selection for satellite missions has become a critical factor in maximizing operational efficiency and ensuring mission success. The proper selection of orbit must consider various factors, including coverage of areas of interest, access times to ground stations, revisit times, and the satellite's orbital lifespan [2].

In the case of Colombia, the Colombian Airspace Force (FAC) has led significant advances in the space domain with the launch of the FACSAT-1 satellite and the co-development of the FACSAT-2 "Chiribiquete" satellite mission. These assets have contributed to the development of capabilities, including data collection from Earth Observation sensors, autonomous satellite operation, as well as capability enhancement in mission design, software development, payload operation, and data analysis applications. These foundations have set the stage for future mission developments in the country.

FACSAT-1, launched in 2018, was the country's first Earth observation satellite, which enabled the autonomous operation of an optical data acquisition system. FACSAT-2, its successor, has improved payload and communication capabilities. The primary payload acquires multispectral images, while a secondary payload collects spectral signatures. These data are used for developments such as deforestation analyses and Greenhouse Gas (GHG) emission monitoring [3] [4].

Currently, a new satellite mission is under analysis, building on the achievements of its predecessors and incorporating technological advancements and lessons learned to optimize performance. This article focuses on the orbit selection for a future satellite mission by analyzing parameters and criteria that ensure a balance between coverage, access times, revisit times, and orbital lifespan, to maximize return on investment. Through simulations and evaluations of different orbital scenarios, this research seeks to identify the best configuration to meet the objectives of a new Earth observation mission with enhanced capabilities to address the country's needs.

To achieve this, a detailed analysis of orbital variables is presented, evaluating inclined orbits and sun-synchronous orbits (SSO) to determine which offers the best balance between coverage and operational efficiency. The results of this research provide a guide for orbit selection in future satellite missions, contributing to the ongoing development of Colombia's space capabilities.

Materials and Methods: Mission and Requirements

Figure 1 presents the methodology developed to select the most suitable orbit by transforming mission requirements, payload constraints, and communication requirements into design variables, thereby establishing the orbital parameters for selection [5].

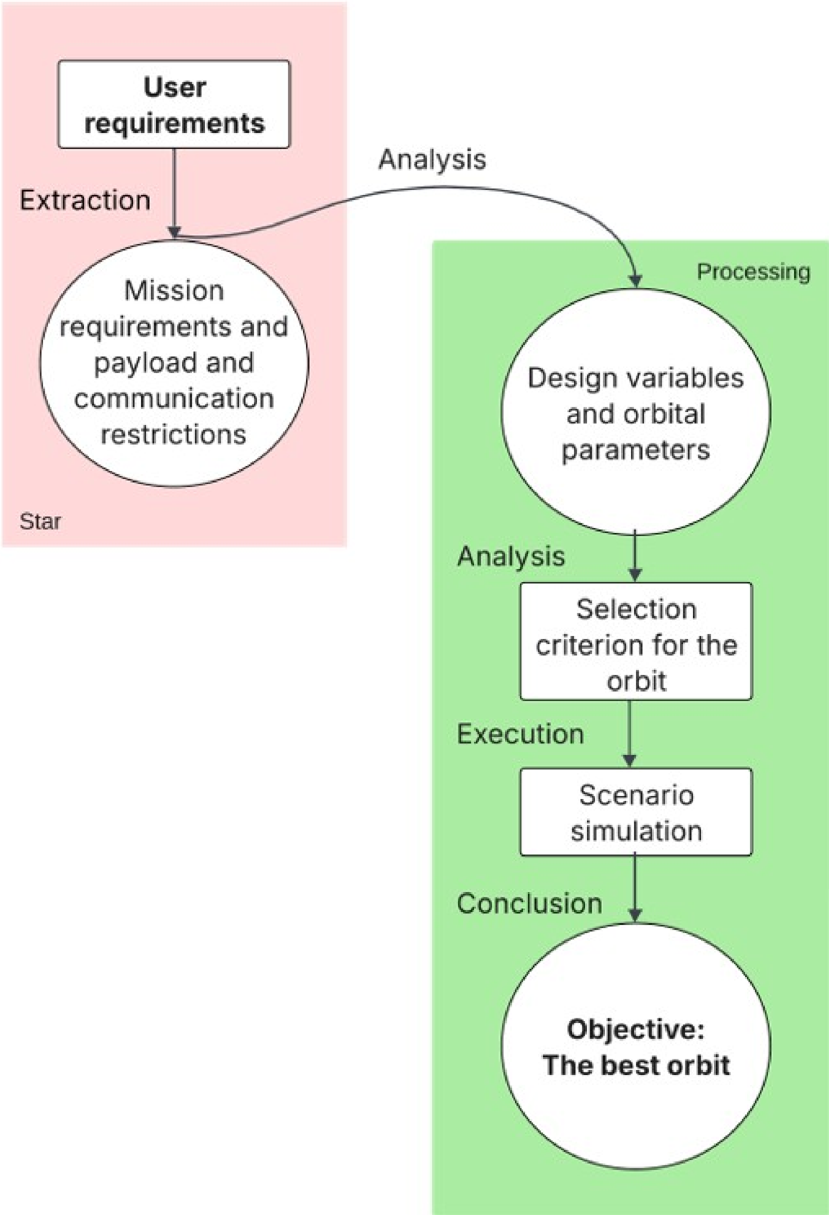

FIGURE 1
Methodology for Orbital Selection
Source: Authors.

The choice of the operational orbit for an Earth observation satellite mission is determined by user requirements, as these guide the design and development of systems that must operate reliably under extreme conditions [6]. Table 1 presents the main mission requirements, including the constraints provided by the payload and communications systems. [5].

Among the mission requirements, some of the most relevant aspects include: the type of orbit and altitude, which determine the range of latitudes available for the satellite to cover; the area of interest; the number of accesses; and the revisit times, which determine what regions on Earth can be studied and how they can be accessed. Lastly, the orbital lifespan refers to how long the satellite can remain in orbit while operating nominally.

Within the payload constraints, the Off-Nadir angle is particularly noteworthy, as it defines the maximum inclination a satellite can achieve from the nadir side while maintaining effective imaging capabilities [7]. The operational time refers to the optimal period during which a sensor can effectively capture data, considering environmental conditions and the orbital trajectory [8].

Finally, among the communication constraints, the elevation angle stands out as a limitation caused by Colombia's mountainous terrain. The minimum access time determines the efficiency of the link between satellites and ground stations, which affects the quality of communication services. [9] [10].

TABLE 1
Mission Requirements and Constraints

Requirements and Constraints	
Mission Requirements	Low orbit type: Inclined, SSO
	Altitude range
	Areas of interest
	Number of accesses
	Revisit times
	Orbital lifetime
Payload Constraints	Maximum Off-Nadir angle
	Operational time
Communication Constraints	Elevation angle
	Minimum access time

Source: Authors.

The criteria outlined in Table 1 are the primary focus for simulating scenarios, allowing the identification of the best orbital aspects that benefit the satellite mission. The aim is to find a way to address and satisfy these requirements [11].

Table 2 lists the design variables and orbital parameters determined from the mission requirements and constraints. These primarily correspond to the type of orbit, the altitude, the inclination, the eccentricity-perigee argument, the RAAN (Right Ascension of Ascending Node), the sensor, the Off-Nadir angle, the revisit time, and the elevation angle.

TABLE 2
Effects of Design Variables and Orbital Parameters on Selection Criteria

Design Variables and Orbital Parameters	Major Effects	Selection Criteria
Type of Orbit	**Coverage of a Region** **Revisit Time** **Eclipse Time**	Inclined Orbit or Sun-Synchronous Orbit (SSO)
Altitude	Coverage	**Image Quality:** < 700 km (based on camera resolution)
	Revisit Time	**Payload Complexity:** > 400 km (lower trajectory speed)
	Image Resolution	Orbital Maintenance and De-orbit
	Eclipse Time	> 430 km (lower ΔV for maintenance)
	Orbital Lifespan	< 530 km (lower ΔV for de-orbit)
Inclination	Coverage by Latitude Distribution	Inclined Orbit: Latitude band coverage for Colombia
	Angular limit with the solar zenith (for optical payloads)	
	Eclipse Time	SSO Orbit: Total coverage, altitude limitation
	Orbital Lifespan	
Eccentricity and Argument of the Perigee	Altitude and Speed (Circular or Elliptical Orbit)	Circular Orbit (Uniform Speed)
	Coverage	
	Orbital Lifespan	
RAAN	Eclipse Cycle	Depends on the launcher
Sensor and Off-Nadir Angle	Complexity in the Satellite Structure	Total Coverage of Colombia
	Revisit Time	
	Overlap Area (Pan-Sharpening)	Minimum Pointing Angle (Offset): ± 7.5° (ADCS mode)
	Coverage	
Revisit time	Coverage	Limitation for Revisit Time (days)
	Offset Angle	
	Communication Times	Communication Limitation: ≥ 5 min (Telemetry Transmission)
	Number of Satellites	
Angle of elevation	Communication Feasibility	Elevation Angle Limitation: ≥ 10° (Geographical Characteristics of the Territory)
	Line of Sight	

Source: Authors.

The variables and parameters have been selected based on their impact on factors of interest for the mission [10], including coverage, orbital lifespan, image resolution, eclipse times, and communication times, among others. The selection criteria arising from the analysis of these factors provide the necessary parameters for simulating various orbital scenarios. Consequently, there will be a specific number of possibilities for the scenarios, and the results will subsequently be analyzed and compared against the selection criteria to identify an orbit with the most favorable aspects for the satellite mission [12].

Results

Design and Simulation (Scenarios)

Based on the selection criteria, three main variables are identified for running the simulations and defining the criteria.

1. Coverage of the Region: to analyze the coverage of the area of interest.
2. Access Times to Ground Stations: to analyze the link times between ground stations and the satellite
3. Orbital Decay: to analyze the satellite's orbital lifespan [13]

The next simulations are focused on each criterion described. To complement each scenario, some simulation parameters must be defined. Table 3 summarizes these elements:

TABLE 3
General Aspects of the Simulation Scenarios

Simulation Start: 04/04/2024 17:00 UTCG	**Simulation Duration:** 1 year
Software: Satellite Tool Kit (STK) and DRAMA	**Simulation Step:** 30 s
Orbital Altitude: 530 km	**Satellite Mass:** 150 kg
Main Payload swath: 19km x 36km	**Secondary payload swath:** 1°

Source: Authors.

In the following paragraphs, the results obtained from each simulation will be briefly presented:

Coverage

This simulation utilizes a defined "rectangular" region to include territories that are not part of the continental section of Colombia, such as the islands, allowing for a comprehensive analysis of its territory.

Orbital Plane 10°

Nadir: In general, Figure 2 shows the coverage of a LEO satellite with an inclination of 10° over one year of simulation. The figure illustrates the number of passes over Colombian territory in the Nadir operation.

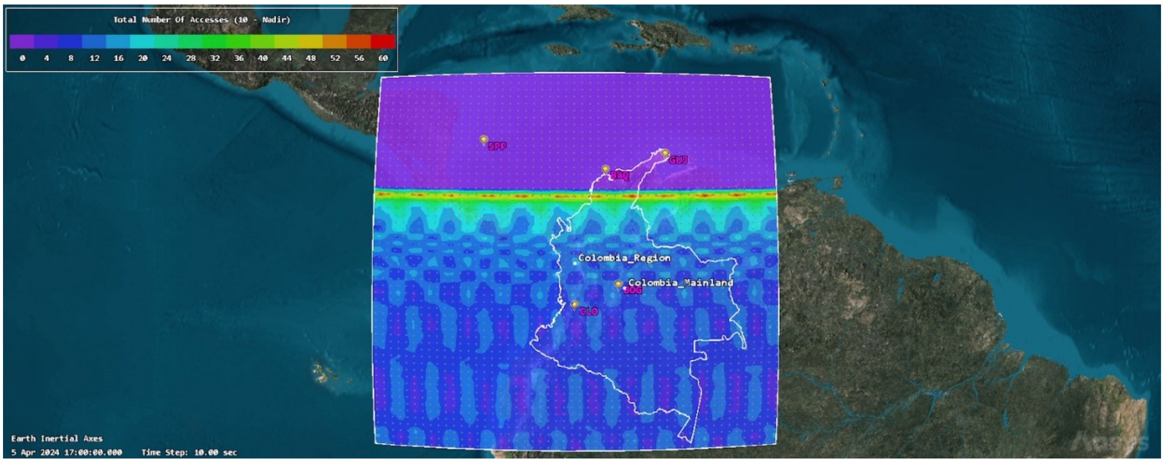

FIGURE 2
Number of Passes for 10° Orbit in Nadir
Source: Authors.

The defined region would receive about 12 passes annually, corresponding to an average frequency of one pass per month. The figure depicts a purple area that represents a region of zero coverage, encompassing Barranquilla, La Jagua, and San Andrés. This limitation would prevent meeting the requirement for complete coverage over Colombia. The area with the highest revisit rate would be at the border of the zero-coverage region, as it represents the perigee/apogee of the orbit.

Oblique: Figure 3 illustrates the coverage simulation, showing the number of passes during the Offset operation

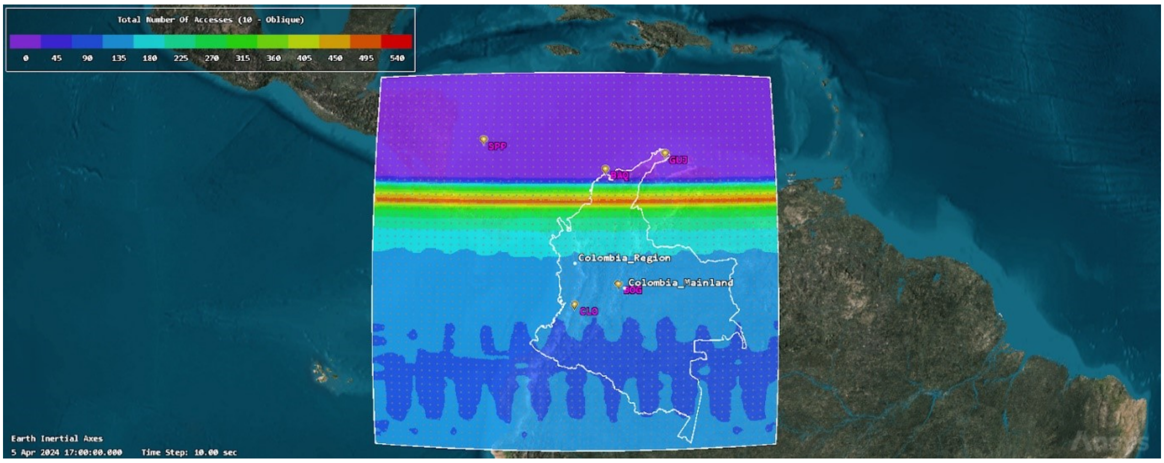

FIGURE 3
Number of Passes for 10° Orbit in Oblique (Offset)
Source: Authors.

By Figure 3, an expansion in the coverage area is observed. However, Barranquilla, La Jagua, and San Andrés remain part of the zero-coverage region. Similarly, the number of passes over the Colombian territory increases, with an average of 135 passes per year (11.25 passes per month).

Orbital plane 16°

Nadir. Figure 4 illustrates the coverage simulation, showing the number of passes during Nadir operation.

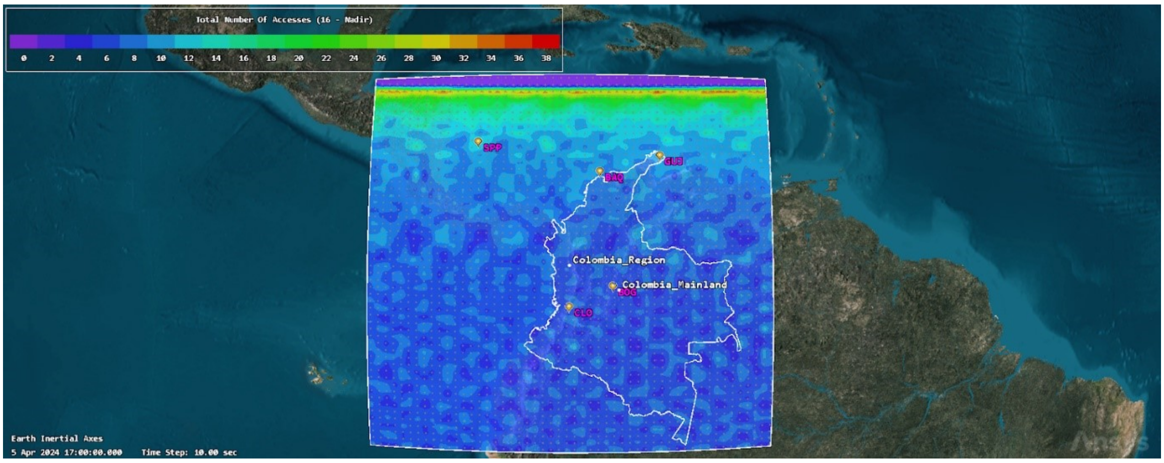

FIGURE 4

Number of Passes for 16° Orbit in Nadir

Source: Authors.

The defined region would have an average of 10 total passes (2 passes per month). There is a region of zero coverage within the defined area, but it is not part of Colombia. The area with the highest number of passes is outside Colombia. Additionally, it is observed that with this inclination and sensor operation, a complete coverage of the Colombian territory is achieved, ranging from 2 to 14 passes.

Oblique. Figure 5 illustrates the coverage simulation, showing the number of passes during the Offset operation.

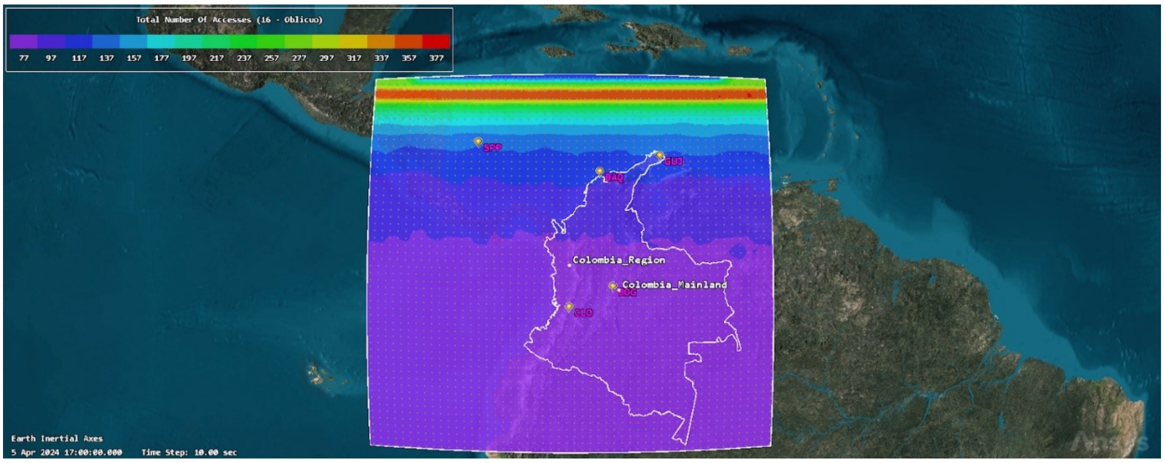

FIGURE 5

Number of Passes for 16° Orbit in Oblique (Offset)

Source: Authors.

In oblique orientation, as illustrated in Figure 5, a greater degree of uniformity is observed in the annual number of passes over the territory, with values ranging from 77 to 117 passes per year. This includes regions such as Barranquilla, La Jagua, and San Andrés. The results indicate that a portion of the territory is expected to have at least 6.42 passes per month, which is similar to the overall average of 11 passes per month. In this case, the region with the highest number of passes does not belong to Colombia.

Orbital Plane 97°

Nadir: Figure 6 presents the coverage simulation results, detailing the number of passes achieved during Nadir operations.

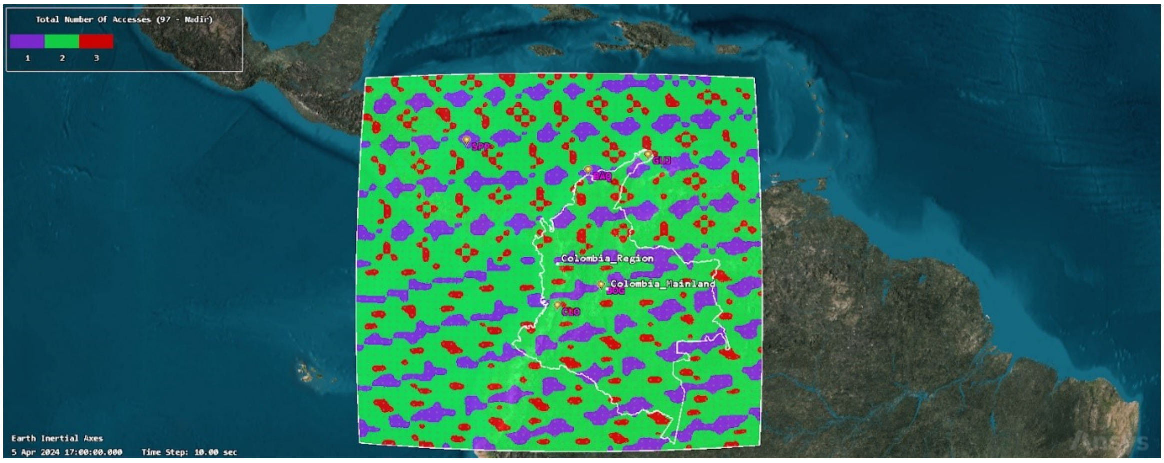

FIGURE 6
Number of Passes for 97° Orbit in Nadir
Source: Authors.

The defined region would have an average of 2 total passes. Observing Figure 6, a high degree of uniformity is noted, with at least 1 annual pass at each point within the defined region, implying a complete coverage of the area. Certain small regions receive only three passes annually, resulting in an average interval of 121 days between passes.

Oblique: Figure 7 illustrates the coverage simulation, the number of passes during the Offset operation.

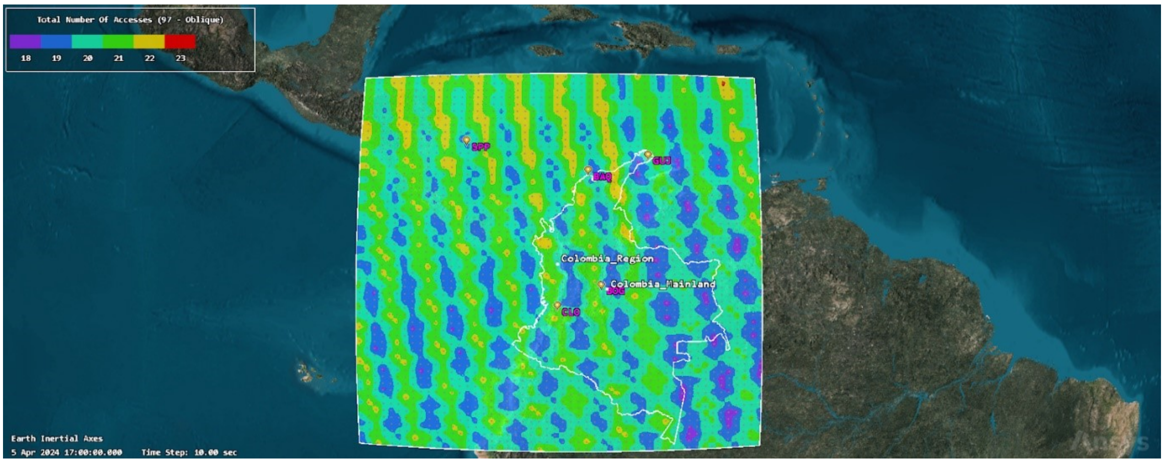

FIGURE 7
Number of Passes for 97° Orbit in Oblique (Offset)
Source: Authors.

As shown in Figure 7, the coverage area expands into a vertical-diagonal band, receiving 18–23 annual passes. The region averages 20 passes per year, or 1.67 per month.

Communication Access

This simulation uses a 50 km grid, with each node representing a ground station in Colombia. For COLAF, key target points include Cali, Bogotá, Barranquilla, La Jagua, and San Andrés, as they are major cities or strategic sites for building a ground segment facility.

Orbital Plane 16°

Average Access Time (s): Figure 8 illustrates the average access times for a 16° inclined orbit.

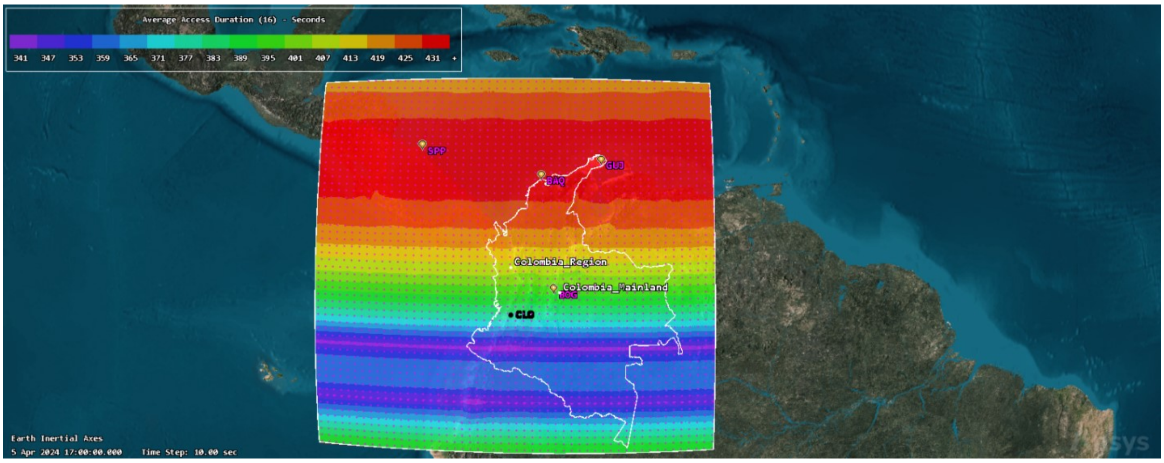

FIGURE 8

Average Access Time for 16° Orbit

Source: Authors.

The average access times in this orbit range from 5.6 to 7.18 minutes, as illustrated in Figure 8. The area with the highest access times is in the north, including BAQ, GUJ, and SPP, while the area with the lowest access times is in the south. The average communication time for the region is approximately 6.58 minutes, while the ground stations in Cali and Bogotá have an average access time of 6.38 minutes.

Maximum Revisit Times (s): Figure 9 illustrates the total revisit times for a 16° inclined orbit.

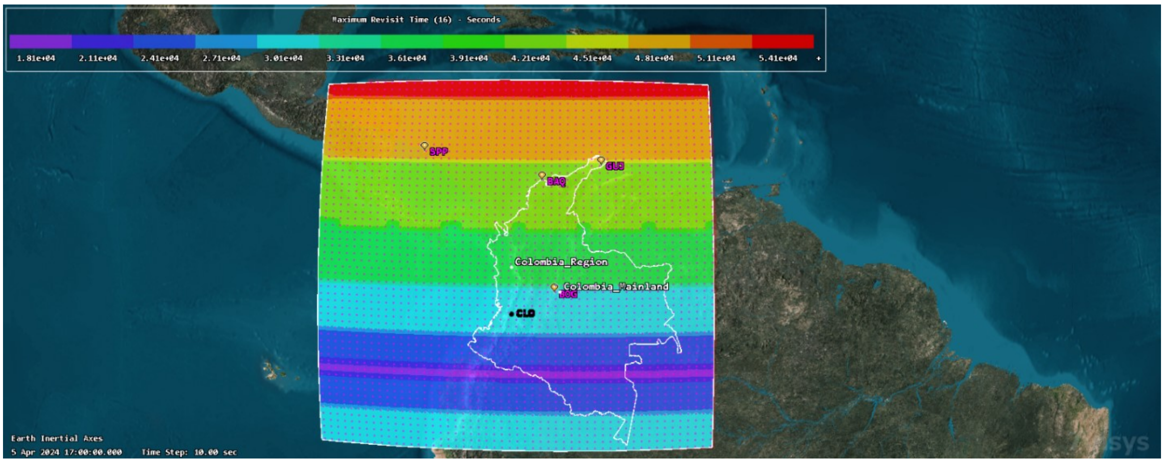

FIGURE 9

Total Revisit Times for 16° Orbit

Source: Authors.

The longest revisit times are found in the northern area of the defined region, with a minimum of 13 hours. The southern zone achieves the shortest revisit times, with a maximum of 6.69 hours, making it the most favorable area for this orbit. The stations in Cali and Bogotá have a revisit time of 8.36 hours, while Barranquilla and La Jagua have a revisit time of 11.69 hours. On average, the territory has a revisit time of 9.2 hours.

Orbital Plane 97°

Average Access Time (s): Figure 10 illustrates the average access times for a 97° orbit.

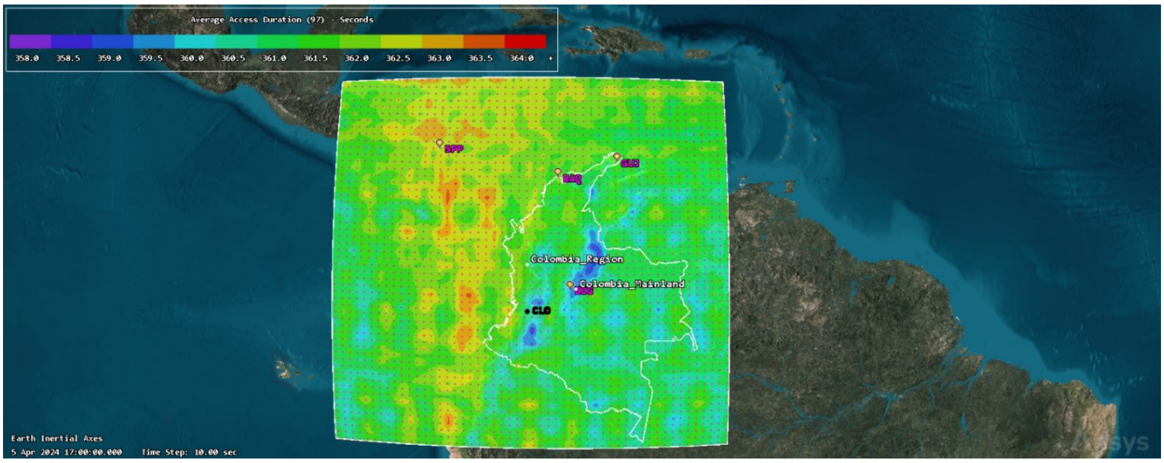

FIGURE 10

Average Access Time for 97° Orbit

Source: Authors.

In this orbit, the average access times are between 5.97 and 6.07 minutes, resulting in a reduced and nearly uniform spectrum across the entire defined region. The Colombian territory has an average access time of approximately 6 minutes, with the ground stations in Cali and Bogotá falling within this average range. The western zone comprises areas with maximum coverage, in which San Andrés is located.

Maximum Revisit Times (s): Figure 11 illustrates the total revisit times for a 97° inclined orbit.

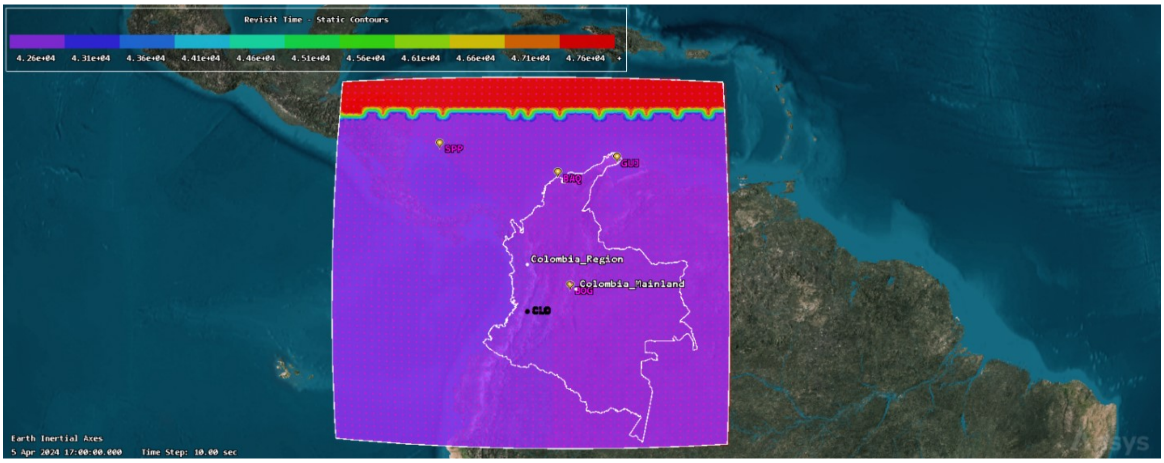

FIGURE 11

Total Revisit Times for 97° Orbit

Source: Authors.

Figure 11 shows the maximum revisit times obtained for this 97° orbit. Where uniformity in revisit times is achieved across the entire Colombian territory, with a duration of 11.83 hours.

Orbital Decay

In this scenario, dimensions sourced from multiple suppliers are used, and the satellites are modeled as rectangular prisms for simulation purposes. Additionally, standard values for the drag coefficient and reflectivity are used, being 2.2 and 1.3, respectively [14] [15] [16]. Table 4 summarizes the results obtained from two simulation software packages: DRAMA and STK.

TABLE 4
Orbital Decay Results in Years

Simulation Parameters						Simulation Results Years)			
Panel Area (m^2)	Model	Surface Area Velocity (m^2)	Drag AREA (m^2)	Sunlit Area (m^2)	Excentricity	Inclination (°)			
						16	97	16	97
0.6675	Option 1	Best case: 0.26109	0.7814	1.0805	0.0001	11.45	14.66	12.2	13.2
	517x801x 505 mm				0.002	11.41	14.53	12.2	13.2
		Worst case 0.41412	0.809	0.92859	0.0001	11.25	14.01	12	12.9
					0.002	11.21	13.88	12	12.9
	Option 2	Best case: 0.555	1.3936	1.5825	0.0001	8.97	9.96	8.4	9.4
	750x740x 1220mm				0.002	8.94	9.93	8.4	9.4
		Worst case: 0.915	1.4268	1.2225	0.0001	8.89	9.86	8.1	9.2
					0.002	8.87	9.83	8.1	9.2

Source: Authors.

In general, it is observed that SSO orbits provide greater longevity compared to orbits near the equator.

Results Analysis

Simulation Results

Coverage Analysis:

- *Relationship between proximity to the equator and number of passes:* Orbits closer to the equator exhibit a greater number of passes over the territory, as observed for orbits with a 10° inclination. However, due to the geometry of their trajectory, these orbits do not cover the northernmost regions of the country. This makes them inadequate for achieving complete coverage of the Colombian territory and, therefore, unsuitable for the mission.
- *Efficiency of the 16° orbit:* The 16° orbit is projected to be the most effective, with part of the area estimated to receive at least 6.42 passes per month, thereby increasing the frequency of territorial imaging.
- *Coverage distribution in the northern region of the country:* There is a general trend toward greater coverage in northern Colombia for a 16° orbit, with the La Guajira region recording the highest number of passes in the entire country.

Communication Access Analysis:

- *Impact of Latitude and Orbital Inclination on Ground Stations:* As the latitude of the ground station increases, fewer passes per day and longer revisit times are observed. Similarly, an increase in orbital inclination results in a reduction in daily passes and an increase in revisit times.

- *Comparison of Orbits in Different Cities:* The orbit with an inclination of 16° is the second-best option for Cali and Bogotá, and the best option for La Jagua and San Andrés. In Barranquilla, the 10° and 16° orbits yield similar results.
- *Overall Performance of the 16° Orbit:* The 16° orbit provides the most frequent daily passes, shorter access times, and reduced revisit intervals compared to other orbits. These parameters support consistent communication between satellites and ground stations in Colombia.
- *Performance of the 97° Orbits:* The 97° orbit presents the shortest communication times, the lowest number of passes per day, and the highest revisit times across all ground stations in Colombia.

Orbital Decay:

- *Debris Mitigation Requirements According to ECSS-U-AS-10C Standard* [17]: The ECSS-U-AS-10C standard—Adoption Notice of ISO 24113: Space Systems—addresses the requirements for debris mitigation and establishes that satellites in low orbit should not operate for more than 25 years. They must also remain inactive for a maximum of 5 years to minimize collision risks. The FACSAT-3 mission meets the specifications outlined in international standards.
- *Orbital Eccentricity and Satellite Lifespan:* Satellites with lower orbital eccentricity, meaning a more circular orbit, tend to have a longer operational lifespan.
- *Comparison of Orbital Lifespan in 16° and 97° Orbits:* Orbits with an inclination of 16° show a shorter orbital lifespan for satellites compared to 97° orbits, with factors such as gravitational field and atmospheric density variation directly influencing these results.
- *Orbital Lifespan Range for the FACSAT-3 Satellite:* In general, the orbital lifespan of the satellite for the FACSAT-3 mission would range from 8.87 to 14.66 years, representing the worst and best cases, respectively.

Results - Selection Criteria

The main criteria selected for the orbit design are the payload constraints, which include resolution, speeds (orbital and satellite) for image capture, offset angle, coverage of the area of interest, and revisit time.

- **Coverage:** It is a key consideration that the designed satellite must cover the entire Colombian territory, including its associated islands. This aspect is achieved with orbits of inclination ≥ 16° and an oblique pointing of ± 7.5° for image capture.
- **Revisit Time:** For operational and communication interests, the shortest revisit times are required. These values are found in orbits with planes close to the equator. These orbits also provide the greatest number of accesses and possible passes for the mission. Therefore, the 16° orbit would have two important, favorable aspects for mission development.
- **Resolution and Speeds for Capture**: The camera resolution depends on the operational altitude range for execution, and each altitude corresponds to a specific orbital speed. Lower orbital speeds are preferable, as they facilitate target capture. Considering these factors, the optimal altitude range for satellite operation is between 430 and 530 km.
- **Orbital Lifespan:** An orbital lifespan greater than 5 years is required for operations. Additionally, the guidelines for space debris mitigation indicate that a maximum lifespan of 25 years should be planned to reduce the risk of collisions in the orbital environment [18] [19] (Compliance for LEO satellites. ISO 27852: 2011). Polar orbits have the longest times in orbit, but this is not as significant compared to quasi-equatorial orbits. Orbital eccentricity influences the duration of an orbital lifespan; orbits

that are more circular (with eccentricity approaching zero) typically result in longer lifespans and more consistent orbital velocities.

- **Elevation Angle:** Based on the geographical features of Colombia, certain ground stations require a minimum elevation angle of 10° to maintain communication with the satellite. Additionally, the communication system specifies a minimum access duration of 300 seconds for data transfer, which is supported by the defined orbital characteristics.

Conclusions: Orbital Selection

After analyzing the previously obtained results, an updated table detailing the orbital requirements for the FACSAT-3 mission is presented below (Table 05):

- Based on the analysis of the simulations conducted, an orbit with a 16° inclination offers the best balance between territorial coverage, revisit time, and access to ground stations for the FACSAT-3 mission. This configuration ensures complete coverage of Colombian territory, including its islands, with an average of 11 monthly passes in oblique mode, and a range between 2 and 14 passes in the Nadir mode.
- The simulations also show that this orbit meets the technical communication requirements (access times between 5.6 and 7.2 minutes per station, elevation angle ≥ 10°, and a minimum contact time of 300 seconds), as well as international regulations on space debris mitigation (ECSS-U-AS-10C). Although SSO orbits at 97° offer longer orbital lifespans, their less favorable revisit and access times make them less suitable for the mission's objectives.
- In terms of payload operation, an altitude between 430 and 530 km is confirmed to optimize image quality and enable suitable orbital velocities for data acquisition. This configuration supports an orbital lifespan between 8.9 and 12.2 years at this inclination, remaining within the range established by international standards.

This table summarizes all the simulations, results, and analyses conducted for the orbital design. This orbit incorporates the requirements for the FACSAT-3 mission and the best aspects for its execution.

TABLE 0 5
Selected Aspects for the FACSAT-3 Mission Orbit.

Requirements and Restrictions	
Mission Requirements	**Type of Low Orbit:** Inclined 16° and Circular
	Altitude Range: [430, 530] km
	Areas of Interest: Entire Colombian Territory
	Number of Accesses: ~ 1 pass per day (coverage)
	Average Revisit Time over Colombia: ≤ 3 h
	Orbital Lifespan: [5, 25] years
Payload Constraints	**Maximum Off-Nadir Angle:** ± 7.5°
	Operational Time: Daytime (solar incidence)
Communication Constraints	**Elevation Angle:** ≥ 10°
	Minimum Access Time: 5 min (300 s)

Source: Authors.

In conclusion, based on the coverage criteria, link times, orbital lifespan, and compliance with international standards, a 16° inclined orbit with both nadir and oblique (±7.5°) operation represents the best option for Colombia's optical microsatellite Earth observation mission.

Acknowledgments

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Notes

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