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Determination of an Operational Orbit for the FACSAT 2 Earth Observation Satellite Mission[a]

Determinación de una órbita operacional para la misión satelital de observación de la tierra FACSAT 2

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Abstract

Objective: *Through the FACSAT program, the Colombian Air Force aims to promote the independence of the Colombian space initiative. This article proposes the operational orbit for the FACSAT-2 satellite mission, intended for capturing images facilitating the detection and classification of Colombian terrain using satellite technology.* ***Materials and Methods****: To advance aerospace technology, this study recommends a specific operational orbit for FACSAT-2. The selection considers operational requirements, geographical location, launch windows, commercial orbit availability, and data from FACSAT-1 and simulated scenarios.* ***Results and Discussion****: The operational orbit is crucial in satellite system design. Restrictions on elevation angles and considerations regarding total accesses, access time, among others, reflect a comprehensive approach, strengthening the foundation for selecting the operational orbit.* ***Conclusions:*** *Criteria for the FACSAT-2 operational orbit were defined, addressing inclination, total accesses, access time, revisit time, altitude, and launch window. Simulations indicate that an inclination ≤ 40° offers optimal performance, with an optimal altitude of 550 km. The orbit with a 23° inclination, 550 km altitude, scheduled for 2022 Q3 from India, stands out for providing maximum accessibility and coverage for Colombia.*

Resumen

Objetivo: *La Fuerza Aérea Colombiana, a través del programa FACSAT, busca impulsar la independencia de la iniciativa espacial colombiana. Este artículo propone la órbita operacional de la misión satelital FACSAT-2, destinada a obtener imágenes que faciliten la detección y clasificación de extensiones de terreno colombiano mediante un satélite.* ***Materiales y métodos:*** *Para avanzar en la tecnología aeroespacial, este estudio recomienda una órbita operacional específica para FACSAT-2. La selección considera requerimientos operativos, ubicación geográfica, ventanas de lanzamiento, disponibilidad de órbitas comerciales, y datos de FACSAT-1 y escenarios simulados.* ***Resultados y discusión:*** *La órbita operacional es crucial en el diseño del sistema satelital. Restricciones de ángulo de elevación y consideraciones sobre accesos, tiempo de acceso, entre otros, reflejan un enfoque integral, fortaleciendo la base para la selección de la órbita operacional.* ***Conclusiones:*** *Se definieron los criterios para la órbita operacional de FACSAT-2, abordando inclinación, accesos totales, tiempo de acceso, tiempo de revisita, altitud y ventana de lanzamiento. Las simulaciones indican que una inclinación ≤ 40° ofrece el mejor rendimiento, con altitud óptima de 550 km. La órbita de 23° de inclinación, 550 km de altitud, programada para 2022 Q3 desde India, se destaca por ofrecer la máxima accesibilidad y cobertura para Colombia.*

Keywords: Orbit; Satellite; Launch; FACSAT-2

Palabras clave: Orbita; Satélite; Lanzamiento; FACSAT-2

Introduction

The satellite mission FACSAT-2 was born out of the desire to achieve autonomous capability for obtaining images of the Colombian territory and is the second of multiple missions that the Colombian Air Force (FAC) intends to develop in the future. Its primary objective is to obtain images that can be used by government entities, private organizations, and academia for monitoring the Colombian territory in scenarios such as natural disasters and surveillance, among other applications.

The challenge for the FACSAT-2 satellite mission is the implementation of a system that allows the acquisition and provision of images facilitating the detection and classification of maritime and continental extensions of the Colombian territory, limited to the use of only one (01) satellite. For this purpose, the determination of the operational orbit of the satellite is one of the components that plays a special role in the satellite system design [1, 2, 3].

The orbit typically defines the life of the satellite mission, determines aspects of communication with the ground station, predicts the coverage of areas under study, and the performance that the payload must achieve for mission fulfillment [1]. In general, the quality of a satellite mission depends on the determination of its orbit [2, 3], and for its selection, a process with multiple compromise relationships between requirements must be carried out to find and recommend the orbit that best meets the mission's objectives [1, 2].

This process does not have absolute rules [1]. Therefore, the utility of this article lies in the in-depth analysis of commercially offered orbit options in which the satellite can operate, taking into account specific factors such as mission requirements, the location, and geographic extent of Colombia, among others. Likewise, the methods used should support decision-making for the upcoming space missions to be carried out in the country.

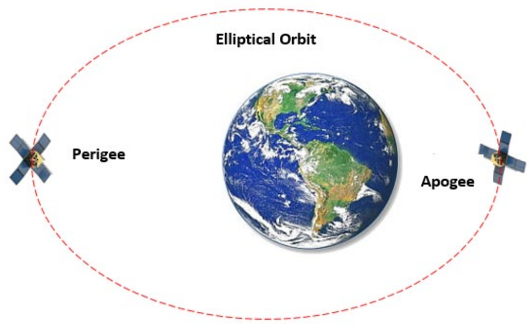
Conceptual Framework

The conceptual framework for this article focuses on themes related to the definition of orbit, the types and classifications it presents, as well as information related to the operational concept of FACSAT-2.

Type of Orbit

The orbit is the path followed by a satellite, and its selection must be considered a priority aspect to ensure the success of the mission [1, 2]. This trajectory occurs within a plane around the Earth with maximum extension at apogee and minimum extension at perigee when the orbit is elliptical, as shown in Figure 1.

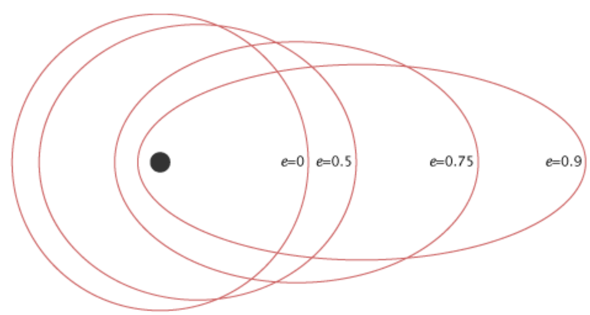
Figure 1. Apogee and Perigee in the trajectory of a satellite.



Source: Own elaboration.

The eccentricity (e), illustrated in Figure 2, defines the shape of the trajectory. Table 1 presents the classification of orbits according to their eccentricity.

Figure 2. Eccentricity of an orbit.



Source: H. Riebeek and R. Simmon, 2009 [4].

Table 1. Classification of orbits according to eccentricity.

Type of orbit	*(e)*	Description
circular	$e = 0$	The satellite moves in a circular trajectory around the Earth, for example, Figure 4 $e = 0$
Elliptical	$0<e<1$	The satellite moves in an elliptical trajectory, where the distance from the satellite to the Earth changes depending on its position in its orbit, for example, Figure 4 $e = 0 – 0,9$
Parabolic	$e = 1$	The satellite has a speed equal to the escape velocity; therefore, it escapes the gravitational force of the planet and travels until its speed relative to Earth is zero, generating a parabolic trajectory.
Hyperbolic	$e > 1$	The satellite has a speed greater than the escape velocity; therefore, it escapes the gravitational force of the planet and continues traveling

Source: M. Capderou, 2014 [2], and H. Riebeek and R. Simmon, 2009 [4].

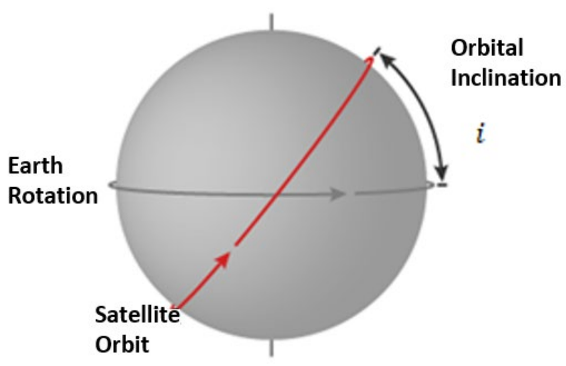
Another way to classify orbits is by their altitude. According to altitude, orbits are classified as Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and High Earth Orbit - Geosynchronous (GEO). The orbit's height or distance between the satellite and the Earth's surface determines how fast the satellite moves around the Earth. While in orbit, the Earth's gravity controls most of the satellite's movement. Therefore, the closer the satellite's trajectory is to the Earth, the faster the satellite will move, approximately at 8 km per second [1,4]. See Figure 3.

Figure 3. Orbit classification by altitude.

Source: Adapted from H. Riebeek and R. Simmon, 2009 [4].

In addition to shape and altitude, orbits are classified by their inclination. The orbit's inclination is the angle between the orbit plane and the equator, measured from the ascending node from the equator to the orbit, in an east to north direction. An orbital inclination of 0° implies that it is directly over the equator, while an inclination of 90° crosses directly over the pole [1,5]. Figure 4 illustrates this concept.

Figure 4. Inclination of an orbit.



Source: Adapted from H. Riebeek and R. Simmon, 2009 [4].

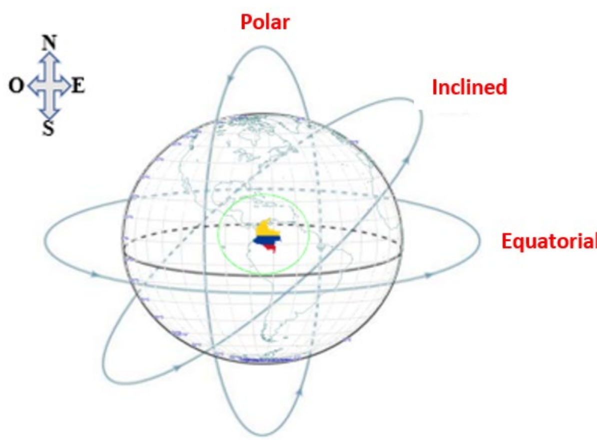
According to their inclination (i), LEO orbits can be classified as: polar orbit, inclined orbit, and equatorial orbit [1, 2]. See Figure 5.

- Polar Orbit: This orbit has an inclination of 90°. In this type of orbit, satellites orbit the Earth in such a way that they cover the southern and northern regions of the planet. If the orbit is between 80° and 100°, it is classified as a near-polar orbit. Most satellites operating in an orbit with an inclination ≥90° take advantage of the condition called Sun-Synchronous (SSO). These orbits combine their inclination and altitude in such a way that an object in these orbits will ascend or descend over any point on the Earth's surface at the same local time, making the illumination angle on the surface almost always the same.

- Inclined Orbit: This orbit has an inclination that is neither 0° nor 90°.

- Equatorial Orbit: This orbit has an inclination of 0° and maintains a trajectory over the equator. If the inclination is less than 20°, it is classified as a near-equatorial orbit.

Figure 5. Orbits according to their inclination.

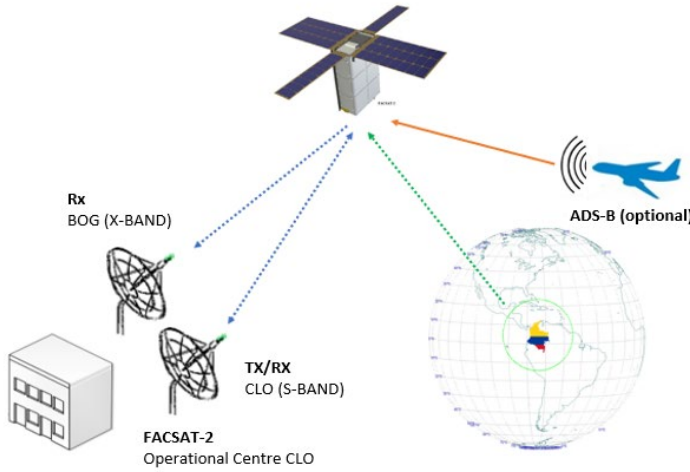


Source: Own elaboration.

FACSAT-2 Mission Statement

The FACSAT-2 mission will strengthen the Colombian Air Force's space initiative and support the satellite image needs of entities with a high level of social impact. It will provide high-resolution multispectral images to support scientific activities and the development of operational capabilities through a satellite with a mass ≤ 10kg. Figure 6 presents the intended operational concept for the satellite mission.

Figure 6. Intended Operational Concept for FACSAT-2 Mission.



Source: Own elaboration (2021).

The overall mission objective is to provide multispectral images that allow the Colombian Air Force, other government entities, and academia to monitor Colombian territory and assess its performance in scenarios such as natural disasters and surveillance, among other applications.

Simulation Tools Available for Orbital Design and Analysis

For the orbital predictions in this article, the tool called Satellite Tool Kit (STK) [6] was used, obtained with permission from Analytical Graphics, Inc. (AGI). This software allows engineers and scientists to perform complex analytical exercises, design system architectures, and simulate trajectories, with applicability in the aerospace, aviation, maritime, and land sectors. Originally created to predict the behavior and make projections of satellites orbiting the Earth, this instrument, with more than 32,000 installations, is now used by the aerospace and defense sectors. Its use is prominent in aerospace organizations such as NASA, ESA, CNES, Boeing, JAXA, Lockheed Martin, Northrop Grumman, EADS, among others, as well as in universities worldwide that teach aerospace engineering [2, 7, 8].

Definition of Criteria for Orbit Selection

In order to define the criteria for orbit selection, the operational information of FACSAT-1 is taken as a reference. FACSAT-1 was launched into orbit from India by the Polar Satellite Launch Vehicle (PSLV) on November 28, 2018, in a Low Earth Orbit (LEO) at approximately 500 km altitude, with a polar inclination of approximately 98 degrees, and in a sun-synchronous orbit. It has been operated by the FAC since then, and there is currently an operational database that allows verifying many of the simulations and considerations made for similar satellite missions such as FACSAT-2.

Table 2. FACSAT-1 Operation Summary

Operation FACSAT-1	
Mission	Earth Observation
# of Satellites	1
Type of Satellite	Nanosatellite, 3U, 10 x 10 x 30 cm, 04 kg. Launch Vehicle ISRO PSLV —2018 Q4 (nov)
Type of Orbit	LEO, Polar (97,6”), Sun-Synchronous
Maximum Altitude of the Orbit	490.914 km
Sensor revisit time over target	≥ 4 días- Oblique Pointing Days
Spatial Resolution	30 m/pixel
# Effective Passes Over Ground Station for Transmission and Reception	≈ 02 /día - transmission and reception
Effective Maximum Communication Range	1950,116 km a 0° elevation 1672,708 km a 10° elevation 1387,024 km a 15° elevation
Obstacle shielding	Elevation angle <15° ≈ 73% probability of communication impairment due to shielding by obstacles
Factor with the greatest influence on communication failure	Meteorology (main effect), Elevation Angle (significance in the connection)
Average Time of Effective	4,748 minutes per satellite revisit
Average revisit time for transmission and reception with the ground station	12,163 hours

Source: Own elaboration

Based on this summary, a series of preponderant factors are presented for the definition of criteria.

Accessibility

Accessibility is defined as the ability to communicate with the satellite and measures the satellite system's performance in terms of the number of accesses, connection time over its ground segment, and average revisit time over a specific target in a given period [1,2,9,10].

Elevation Angle

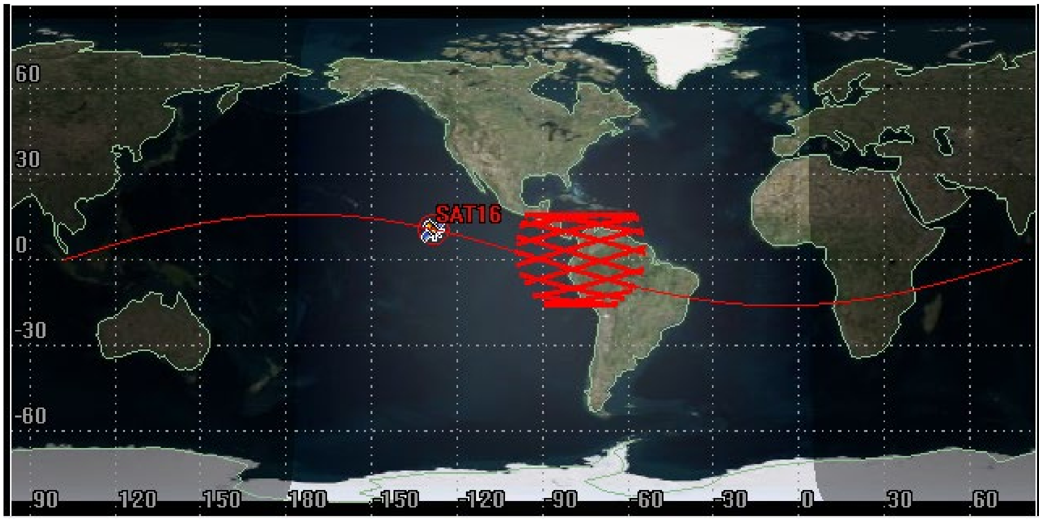
The elevation angle is one of the main determinants of the coverage time of a single satellite over the ground station. The lower the elevation angle, the greater the coverage range, resulting in more access time over the ground station. It can be inferred that the ideal minimum elevation angle to avoid shielding by natural obstacles and buildings is between 2° and 15° approximately [11,12,13].

Orbital Inclination Angle

The orbital inclination angle determines the distribution of latitudes for satellite coverage [2]. To calculate the minimum inclination angle over the territory, Colombia's total surface area is defined as 2,070,408 km², composed of 928,660 km² of maritime extension and 1,141,748 km² of territorial or continental extension [14].

In 2016 [15] determined that a minimum inclination of 16° allows the vertical passage of a satellite over the entire national territory based on border data from the year 2011. Identifying the current border limits published on the official map of Colombia and the border delimitation of the Ministry of Foreign Affairs [16,17,18], it is identified that the southernmost point of the country is located at latitude -4°12'30” S and longitude -69°56'37” W, corresponding to the point where the San Antonio stream flows into the Amazon River, and the northernmost point is located at latitude 16°10'10” N and longitude -79°16´40”, corresponding to Bajo Alicia. Therefore, it is confirmed that a minimum inclination of 16° will guarantee the passage of the FACSAT-2 satellite over the entire Colombian territory. Figure 7 presents a coverage simulation of a satellite, including the ground track with a 16° inclination orbit over Colombian territory.

Figure 7. Orbit coverage with 16° inclination over Colombian territory.



Source: Own elaboration, image courtesy of AGI.

In addition to accessibility and coverage requirements, lighting conditions must be taken into account. Sun-synchronous orbits combine inclination (i ≈ 97° - 99°) and altitude (h ≈ 400 km – 900 km) to maintain their geometry with respect to the sun, so that solar illumination along the satellite's path remains approximately constant during the mission [2,19,10]. Unlike sun-synchronous orbits, inclined orbits induce a variation in lighting conditions for targets during the satellite's passage [2].

Although sun-synchronous orbits are the most used to date for Earth observation applications due to their constant lighting conditions and global coverage [4,2,20], there are studies such as those conducted by [9] and [21], and Earth observation satellite missions such as India-France's MEGHA-TROPIQUES, Malaysia's RAZAKSAT / MACSAT-A, Indonesia's LAPAN-A2, Singapore's TeLEOS-1, VELOX-CI, and Kent Ridge 1, among others, that have used inclined orbits to meet requirements and limitations related to coverage and improve access time to targets in their territory with different lighting conditions.

Altitude

According to its altitude, the satellite will orbit at a higher or lower speed around the Earth. Likewise, the effect of drag or friction with the atmosphere (atmospheric resistance) will have a greater impact on LEO orbits, especially below 650 km altitude [1,10,22]. Therefore, altitude has an effect on accessibility and orbital lifetime.

Taking into account the information reported on the generalities of the FACSAT-2 mission, the operational analysis of the FACSAT-1 satellite, and the identified preponderant factors, 02 workshops were conducted with FACSAT-1 satellite operators.

As a result of these activities, Table 3 presents the key criteria defined for the determination of commercial operational orbits candidates for the FACSAT-2 mission.

Table 3. Key criteria for determining a commercial operational orbit for the FACSAT-2 mission.

ID	Name	Effect	Orbit Selection Criteria
C1	Inclination	Determines the distribution of latitudes for coverage	The selected orbit should have an inclination ≥16° to ensure 100% coverage of Colombian territory.
C2	Total accesses over the ground segment	# of opportunities the satellite has to communicate with the ground segment within a time period.	The highest number of accesses over the ground segment in a year. Ground Station 1: CLO Ground Station 2: BOG Minimum elevation angle: 15°
C3	Ground Segment Access Time (Transmission and Reception)	Total access time (communication) that the satellite has over a ground station within a time period	The longest total access time over the ground station in a year. Ground Station 1: CLO Ground Station 2: BOG Minimum elevation angle: 15°
C4	Average revisit time over target	Average time the satellite revisits a specific target within a given time period, constrained by sensor characteristics	The lowest average revisit time over a target in a year. Target 1: Serranía de Chiribiquete National Park (target point: 0.7460° N; 72.7386° W) Target 2: Cayo Alburquerque (target point: 12.5567° N; 81.71° W) Sensor: captures Off-Nadir (oblique) angles up to 45°
C5	Altitude	Determinant of accessibility and lifespan	C5.1. The selected LEO orbit should be at an altitude that ensures the longest total access time over the ground station and the shortest average revisit time over the target in a year
			C5.2 Orbital lifespan: ≥ 5 and ≤ 25 years
C6	Launch Window.	Launch opportunity within the scheduled time window for the satellite mission	The launch provider must ensure the satellite's orbital placement within the launch window of 2022 Q2 – 2023 Q4

Source: Own elaboration

Available Commercial Orbits

The selection of the orbit is a process that is affected by the availability and commercial offers to meet the stated mission requirements.

The technical requirements made are summarized in Table 4. Table 5 presents 10 selected commercial orbit proposals as of January 2021, considering that they meet the requested technical requirements.

Table 4. Technical requirements made to launch providers and agents

Aspect	Description
Number of Satellites	01
Mass	10 kg
Volume	30 x 20 x 10 cm (6U cubesat)
Launch Type	Shared Launch (RideShare/PiggyBack)
Altitude	Low Earth Orbit LEO
Inclination	≥16°
Launch Window	2022 Q2 – 2023 Q4

Source: Own elaboration is concluded that the commercial orbits presented in the proposals correspond to circular, low Earth orbits with different degrees of inclination and altitude. Polar sun-synchronous orbits (SSO) are the ones with the highest offer and availability with different launch providers. Inclined orbits are offered in smaller quantities than SSO, however, it is evident that for the launch period of the FACSAT-2 mission, there is a variety of options with different launch opportunities to be evaluated.

Table 5. Commercial orbits offered for the FACSAT-2 mission cut-off January 2021.

Type	Inclination (°)	Altitude (Km)	Launch vehicle*'	Manufacturer	Launch Site (country - area)	Reliability *	RideShare Cost (LSD - Includes dispenser)	RideShare Launch Opportunity 2022Q2-2023Q4
Circular LEO	98SSO	500-550	FALCON-9	SPACEX	EEUU-Cabo Cañaveral	99%	280000 - 460000	Up to 9 launches.
Circular LEO	51.65	400	FALCON-9 ISS Despliegue***	SPACEX	EEUU-Cabo Cañaveral Guyana Francesa -	99%	250000 - 330000	Up to 6 launches.
Circular LEO	98SSO	500-550	R-7/ SOYUZ FG. 2-la, 2-lb	Russian Space Agency (Roscos mos) -Russian TsSKBProgress	Kourou. Rusia- Plesetsk Kazajistán - Baikonur	96%	280000 - 460000	Up to 6 launches.
Circular LEO	98SSO	500-550	PSVL	Indian Space Research Oiganisation ISRO	India - Sriliarikota	93%	280000 - 460000	Up to 5 launches.
Circular LEO	23	500-550	PSVL	Indian Space Research Organisation ISRO	India - Sriliarikota	93%	280000 - 460000	Single launch scheduled for 2022-Q3
Circular LEO	51.65	500	ANTARES ISS Despliegue + Cygnus****	NORTHROP GRUMMAN	EEUU-Islas Wallops	90%	280000 - 360000	Up to 4 launches.
Circular LEO	98SSO	500-550	ELECTRON	ROCKETLAB	Nueva Zelanda • Mahia	88%	480000 - 550000	Up to 6 launches.
Circular LEO	40-45	500-550	ELECTRON	ROCKETLAB	Nueva Zelanda • Mahia	88%	480000 - 550000	Up to 5launches.
Circular LEO	98SSO	500-550	VEGA	Italian Space Agency - AVIO	Guyana Francesa - Kourou	88%	300000-480000	Up to 3 launches.
Circular LEO	98SSO	500-550	SOYUZ -2-1 V	Russian Space Agency (Roscosmos) - Russian TsSKBProgress	Rusia - Plesetsk Kazajistán -Baikonur	80%	280000 - 460000	Up to 3 launches.
♦ Reliability from the start of operation based on Lewis point estimate. ♦♦ Approximate range for illustration purposes only. Does not include insurance, transportation expenses, export/import duties, testing, etc.					♦♦♦ Logistics supply to ISS from where the satellite is deployed. ♦♦♦♦ Carried from ISS to 500 km altitude by the CYGNUS spacecraft			

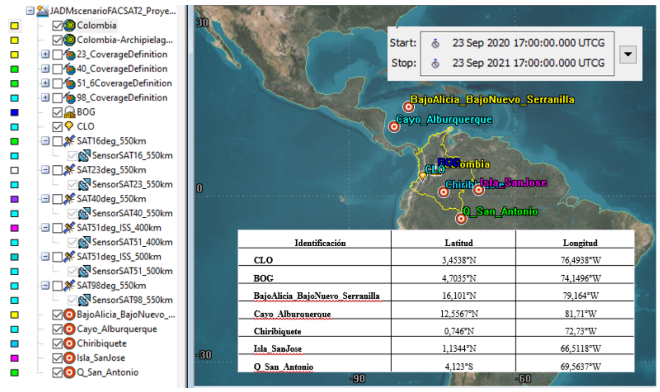
Source: Own elaboration

Simulation

In this section, the general configuration for the simulations performed with the STK software is presented.

To set up the simulation, the study resources represented in Figure 8 were entered, highlighting that the object of analysis is located over Colombian territory. The altitude data for each reference point are automatically identified by the terrain database included in the software. Additionally, a simulation period of one year was established to obtain consistent results.

Figure 8. Simulation Configuration in STK.



Source: Own elaboration image courtesy of AGI

Considering the summary of available launch offers for the mission, it is deduced that there are 07 possible scenarios to study, as shown in Table 6, for the STK simulation using the configuration developed in this section.

Table 6. Identification of scenarios according to commercial orbits available in the launch window.

Scenario	Inclination (°)	Altitude (km)
1	23	500
2	23	550
3	40	500
4	40	550
5	51,6	400
6	51,6	500
7	98 SSO	500
8	98 SSO	550

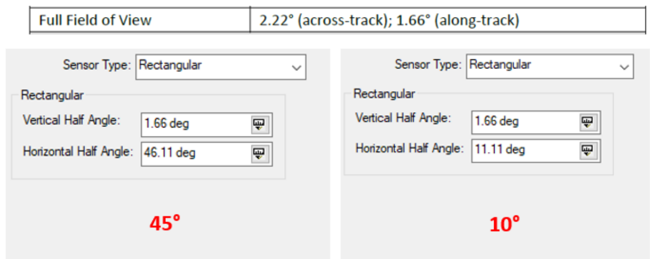
Source: Own elaboration (2021)

For scenario configuration, the STK software provides orbit propagators. The purpose of these propagators is to predict the position of a satellite. For the accessibility simulations (selection criteria C2-C4 in Table 3) of this article, the J4 analytical propagator was used. Its solutions are based on Keplerian elements, include point-mass effects and asymmetry in the gravitational field, and consider the effect of Earth flattening [11,23], which is one of the main perturbations to consider for Earth observation satellites [24,25,26,27].

For trend analysis related to selection criteria C2 and C3, a minimum elevation angle restriction of 15°, following the FACSAT-1 precedents, was included. Also, accesses with a duration of less than 60 seconds were not taken into account.

For trend analysis related to selection criterion C4, a rectangular sensor was included, with a movement range of up to 45° off-nadir (oblique - non-vertical) according to the proposals for the FACSAT-2 mission. However, the higher the camera angle, the more image processing will be required due to distortion [28]. Therefore, simulations were conducted with camera inclination angles of 45° and 10°, as presented in Figure 9.

Figure 9. Sensor properties incorporated for selection criteria C3 and C4.



Source: Own elaboration, image courtesy of AGI.

Finally, for trend analysis related to selection criterion C5, the High-Precision Orbit Propagator (HPOP) was used. For its use, the satellite and orbit characteristics to be analyzed must be entered. Then, the software calculates the effects by applying these characteristics along with available atmospheric density and solar flux models. Taking into account the recommendations made by [29] and [30], Table 7 presents the specifications used for this analysis.

The assumptions and simplifications made to produce a practical computer implementation of the theory introduce a degree of uncertainty into the final result. Additionally, due to the seemingly random variation of atmospheric density and the difficulty of accurately predicting solar activity, the results obtained for orbital lifetime analyses will not be better than +10% of real life [31,32].

Table 7. Specifications used in STK analysis of FACSAT-2 mission orbital lifetime.

Specification	Value / Reference
Volume (HxWxL cm^3)	30x20x10 = 6000 cm^{3*}
Mass (Kg)	10
Drag Coefficient Cd	2,2
Solar Reflectance Coefficient Cr	1,0
Sunlit Area (HxW cm^2)	600*
Resistance Area (cm^2)	600*
Atmospheric Model and Solar Flux	NRLMSISE 2000 …y SolFlx_CSSI.dat
Orbit Type	According to scenarios 1 to 8

Configuration with solar panels undeployed. This value may change depending on the specifications of the solar panels to be used and their mode of operation, which affect the orbit propagation

Source: Own elaboration

Results

In this section, tables and graphs with the results obtained in the simulated scenarios from the previous section are presented for each of the defined criteria.

Criterion C1 – Inclination

This criterion determines the distribution of latitudes for coverage and it was defined that the orbit should have an inclination ≥16° to guarantee 100% coverage of Colombian territory. Therefore, it is concluded that the 8 evaluated scenarios meet this requirement.

Criterion C2 – Total Accesses over Ground Segment

This criterion determines the number of opportunities the satellite has to communicate with the ground segment in a specified period, and it was defined that the orbit should offer the highest number of accesses to each ground station in a year CLO and BOG.

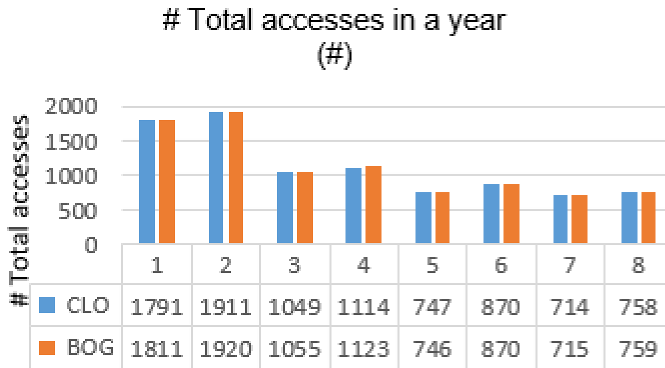
Table 8. Evaluation of Criterion C2 in one year.

	CLO		BOG	
	Maximum	**Minimum**	**Maximum**	**Minimum**
Total number of accesses (#)	1911	714	1920	715
	Scenario 2	Scenario 7	Scenario 2	Scenario 7

Source: Own elaboration

Table 8 presents scenarios with maximum and minimum performance for this criterion obtained from the simulation. The parameters of the orbit for scenario 2 offer the highest number of accesses to CLO and BOG ground stations in a year, with a total of 1911 and 1920 opportunities, respectively. The lowest number of accesses was obtained for scenario 7, resulting in 714 opportunities over CLO and 715 over BOG. The simulation results for all 8 scenarios are presented in Figure 10. For scenarios 1 to 4, it is deduced that the lower the orbit inclination, the greater the number of accesses.

Figure 10. Total accesses to the ground segment in one year.



Source: Own elaboration

Criterion C3 - Total Access Time over Ground Station

This criterion determines the communication time that the satellite has over a ground station in a given period. It was defined that the orbit should provide the longest total access time over the ground segment in a year. Therefore, this performance was evaluated for each scenario over the CLO and BOG ground stations.

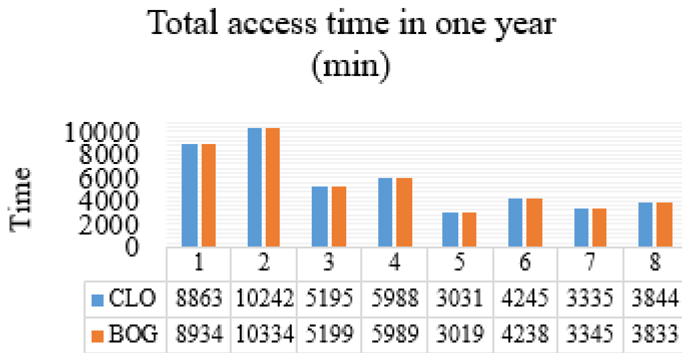
Table 9. Evaluation of criterion C3 in one year

	CLO		BOG	
	Maximum	**Minimum**	**Maximum**	**Minimum**
Total access time in a year (min)	10241,828	3031,452	10333,958	3018,748
	Scenario 2	Scenario 5	Scenario 2	Scenario 5

Source: Own elaboration

The orbit parameters of scenario 2 produce the longest total access time over the CLO and BOG ground stations in one year, 10,242 and 10,334 minutes, respectively. Meanwhile, the simulation results using scenario 5 present the shortest time with 3,031 minutes for CLO and 3,019 minutes for BOG. In addition, the simulation results for the 8 scenarios are presented with rounded values in Figure 11, showing that lower orbit inclination results in longer communication time with the ground segment.

Figure 11. Total access time to the ground segment in one year



Source: Own elaboration

Criterion C4 - Average Revisit Time to the Target

It was stipulated that the orbit should provide the shortest average revisit time to the target in one year. Therefore, this factor was analyzed in simulations with camera inclination angles of 45° and 10° over the targets Serranía de Chiribiquete National Park (target point 1: 0.7460° N; 72.7386° W) and Cayo Alburquerque (target point 2: 12.5567° N; 81.71° W).

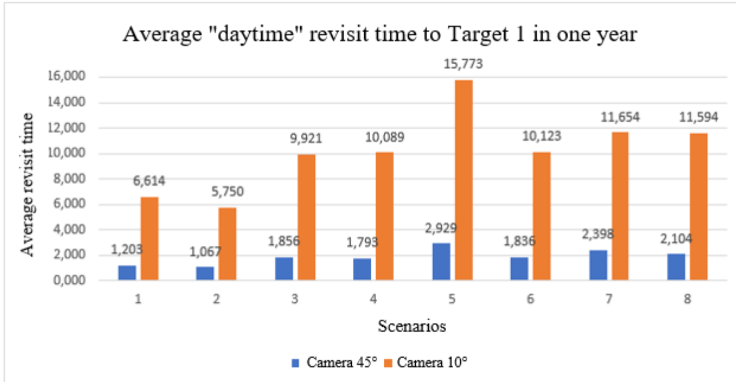
Table 10. Evaluation of criterion C3 in one year

	Objective 1		Objective 2	
	Maximum	Minimum	Maximum	Minimum
Average revisit time (day)	6,537	0,460	6,349	0,369
	Scenario 5 camera @10°	Scenario 2 camera @45°	Scenario 5 camera @10°	Scenario 2 camera @45°

Source: Own elaboration

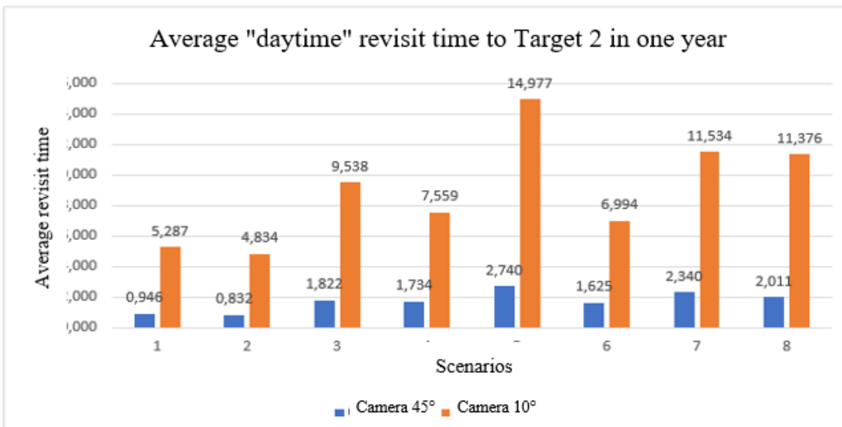
Table 10 presents the overall results obtained from the simulation. The orbit parameters of scenario 2 with a camera inclination angle of 45° produce the shortest average revisit time to targets 1 and 2 in one year, 0.460 and 0.369 days, respectively. The longest average revisit time was obtained for scenario 5 with a camera inclination angle of 10°, resulting in an average of 6.537 days for target 1 and 6.349 days for target 2. The simulation results are presented in Figures 12 and 13. It is deduced that for inclined orbits, the closer the latitude of the target is to the orbit inclination from which access is attempted, the better revisit time is obtained. Additionally, it is confirmed that a lower camera inclination angle results in a longer average revisit time.

Figure 12. Average "daytime" revisit time to Target 1 - Serranía de Chiribiquete National Park in one year



Source: Own elaboration

Figure 13. Average "daytime" revisit time to Target 2 - Cayo Alburquerque in one year



Source: Own elaboration

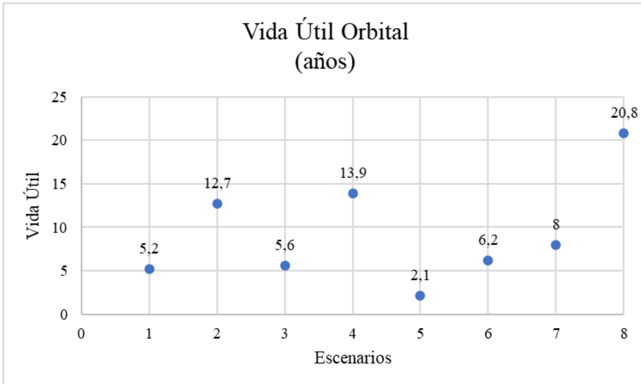
Criterion C5 - Altitude

The selected LEO orbit should be at an altitude that ensures the longest total access time over the ground station and the shortest average revisit time to the target in one year. Considering the results presented in criterion C3, it is evident that lower inclination and higher altitude result in longer total access time over the ground segment. Therefore, the orbit parameters of scenario 2 (23° inclination @ 550 km altitude) offer the best performance with 10,333.958 minutes of total access time over the BOG ground station.

Regarding orbital lifetime, criterion C5.2 requires that the orbit has a lifetime ≥ 5 years, and in compliance with ISO 24113:2019, it is estimated that the satellite in LEO orbits will re-enter the Earth's atmosphere within 25 years after the completion of its mission.

The simulation results for the 8 scenarios are presented in Figure 14. Likewise, Table 11 shows the results of the evaluation of this criterion. The longest orbital lifetime was obtained for scenario 8, corresponding to 20.8 years, and the shortest was obtained for scenario 5 with 2.1 years. Scenarios 1, 2, 3, 4, 6, 7, and 8 meet the criteria for orbital lifetime and component lifetime.

Figure 14. Orbital lifetime.



Source: Own elaboration

Table 11. Simulation results of orbital lifetime for scenarios 1 to 8

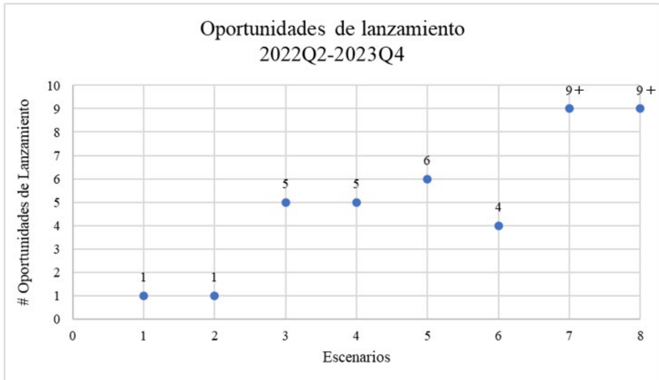
Scenario	Inclination (°)	Altitude (km)	Orbital Lifespan (years)	# Orbits	Meets ≥ 5 years of useful life	Complies with ISO 24113:2019 (assumes ≤25 years)
1	23	500	5,2	29316	SI	SI
2	23	550	12,7	70894	SI	SI
3	40	500	5,6	31343	SI	SI
4	40	550	13,9	77825	SI	SI
5	51,16	400	2,1	12213	NO	SI
6	51,16	500	6,2	35133	SI	SI
7	98	500	8	44903	SI	SI
8	98	550	20,8	115955	SI	SI

Source: Own elaboration

Criterion C6 - Launch Window

This criterion determines the launch opportunity within the established time period for the satellite mission. It was defined that the launch service provider should ensure the satellite's placement in orbit within the launch window of 2022 Q2 - 2023 Q4. In reference to the mission requirements imposed by the FAC, the 8 proposed scenarios meet this selection criterion, considering that the selected commercial orbits were offered for that time period with a different number of opportunities, summarized in Figure 15.

Figure 15. Launch opportunities for commercial orbits offered with a cut-off in January 2021



Source: Own elaboration

Conclusions

As a result, six criteria were defined. The first corresponds to inclination, whose effect determines the latitude distribution for coverage, confirming that the orbit should have an inclination ≥16° to guarantee 100% coverage of Colombian territory. The second corresponds to total accesses over the ground segment, defining the number of opportunities the satellite has to communicate with the CLO and BOG ground stations in one year. The third corresponds to the total access time (communication time) that the satellite has over the ground segment. For criteria 2 and 3, it was determined that an elevation angle restriction of 15° for CLO and 16° for BOG will ensure communication without obstruction from natural obstacles. The fourth criterion corresponds to the average revisit time to the target, whose effect determines the average time the satellite takes to access a target again, limited by sensor characteristics. The fifth corresponds to altitude, whose effect determines accessibility and orbital lifetime. Finally, the sixth criterion corresponds to the launch window, whose effect determines the launch opportunity within the established time period.

The simulation results indicate that, to guarantee maximum accessibility and coverage of Colombia with a single satellite unit, the closer the orbit inclination is to the country's latitude of 16°, the better capabilities will be obtained. The best performance was evidenced for orbits with inclination ≤ 40°. For these orbits, it can be inferred that the closer the latitude of the ground station and the target is to the orbit inclination, the longer access time and shorter revisit time will be obtained. However, these orbits may present variations in lighting conditions for image capture and fewer launch opportunities compared to SSO orbits. Also, regarding altitude, it was determined that an altitude of 550 km offers the best solution. Finally, regarding orbital lifetime, it was concluded that it is directly related to the altitude and inclination of the offered orbits.

Consequently, taking into account the defined selection criteria, available commercial orbits, and the simulation configuration established in this article, it was determined that scenario No. 2, corresponding to the operational commercial orbit with 23° inclination, 550 km altitude, whose only launch opportunity is planned for 2022 Q3 with the PSVL launcher from India, is the orbit that, as of the closing date of this article, is the most favorable, offering the following capabilities: the highest number of accesses over the ground segment (communication) in one year, between 1911 and 1920 accesses; the longest total access time over the ground segment in one year, between 10,243 and 10,334 minutes; the shortest average daytime revisit time to the target in one year, between 0.83 and 5.75 days; 100% coverage of Colombian territory and regions in the world located between latitudes 23°S and 23°N.

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