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Simulation of LEO Cubesat Constellation for Disaster Early Warning

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Abstract

The rapid expansion of Low Earth Orbit (LEO) satellite Technology offers new opportunities for is-land nations to build robust and autonomous communications infrastructure; however, research specifically examining the advantages of the 0° equatorial orbit for CubeSat constellations remains very limited despite its natural suitability for countries located along the equator. This study introduces a new constellation architecture optimized for the equatorial region, specifically Indonesia, by designing and simulating a ten-satellite 3U CubeSat system operating in a 0° equatorial orbit at 600 km. Using AGI Systems Tool Kit (STK) v11, we modeled orbital dynamics, Voice Repeater (VR) and Auto-matic Packet Reporting System (APRS) communication performance, and Inter-Satellite Link (ISL) stability from October 8 to 31, 2025, with a resolution of 30 seconds. The results show an average of 14 daily passes with a contact duration of 770 seconds and a link margin of 3.2 dB, enabling near real-time tactical communications. The main novelty lies in demonstrating that the 0° equatorial LEO constellation provides superior spatiotemporal consistency for Indonesia and can be implemented in other equatorial countries such as Brazil, the Democratic Republic of Congo, Uganda, and others, when compared to CubeSat designs in orbits above 0°. ISL connectivity achieved 99.1% reliability over 23 days, confirming continuous data flow even under ground segment disruptions. This study provides the first integrated demonstration of a VR, APRS, and ISL CubeSat network specifically optimized for equatorial regions, offering a viable and scalable model for disaster early warning systems in island nations. These findings indicate that equatorial orbit CubeSat constellations can serve as a strategic foundation for low latency, sovereign communication infrastructure in Indonesia and other developing countries that are rapidly advancing in the space sector.

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Keywords: Low Earth Orbit (LEO), Cubesat, Satellite, Constellation, Disaster, Early Warning System, Real Time Communication, Inter Satellite Link (ISL).

INTRODUCTION

The development of Low Earth Orbit (LEO) satellite technology has driven significant transformation in global communication systems and improved the effectiveness of disaster early warning mechanisms (Cheng et al., 2021). LEO satellite constellations offer low latency, wide coverage, and continuous connectivity, making them a strategic solution for strengthening communication infrastructure in archipelagic regions such as Indonesia (Qu et al., 2017). In the context of disaster management, the existence of a robust, adaptive, and highly resilient space-based communication system is an important factor in ensuring the flow of real time information between command centers, emergency response agencies, and affected communities (Supriyadi et al., 2019; Djuyandi, Casnoto and Hidayat, 2019; Su et al., 2019)

Most previous research has focused on LEO satellite applications for civil and educational communications, with little attention to dual-use applications for defense and disaster mitigation. Recent global studies show the acceleration of large constellation projects such as Starlink, OneWeb, Telesat Lightspeed, and China's Guowang, which integrate laser based Inter Satellite Links (ISL) to expand network coverage and resilience (Chen et al., 2021; Henry Jiménez et al., 2019; Khalife et al., 2022)The effectiveness of LEO-based early warning systems is highly dependent on the integration between the space segment and the ground segment. Therefore, the design of an optimal LEO constellation, including the number of satellites, orbit configuration, and ISL, is a key factor in ensuring the reliability and continuity of communication networks.

Based on these gaps, this study proposes a simulation framework for designing and evaluating LEO smallsat constellations and ground segment architectures that support space-based early warning systems. The simulation was conducted using Analytical Graphics Inc Systems Tool Kit (AGI STK) 11 to assess communication performance, coverage of Indonesia, and the dynamics of links between satellites and ground stations (Kim et al., 2018)This model also integrates Voice Repeater (VR) and Automatic Packet Reporting System (APRS) payloads to improve emergency communication reliability. This approach is expected to contribute conceptually and practically to the development of disaster mitigation communication systems.

This research also provides a replicable simulation framework that bridges tactical communication needs and national defense autonomy through a small LEO satellite architecture. Although LEO based communication systems such as Iridium NEXT, OneWeb, and Starlink have

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demonstrated global performance with wide coverage and low latency (Christensen et al., 2025) these systems still have fundamental limitations in the context of national disaster early warning systems in archipelagic regions such as Indonesia. First, communication latency and dependence on global gateways cause delays in the transmission of tactical data that is crucial for disaster operations (Can et al., 2025) Second, coverage redundancy in equatorial regions is still not optimal because the polar orbit configuration of global systems does not provide maximum track density at low latitudes (Bonyan, 2008)Third, the tactical resilience of commercial systems is limited because the control infrastructure and ISL (Inter Satellite Link) are not designed for autonomous operations without ground segment support (G. Wang et al., 2024)

This research addresses these gaps through the development of a LEO constellation simulation model with an equatorial orbit configuration of 600 km and an inclination of 0° that integrates two types of payloads, namely Voice Repeater (VR) and Automatic Packet Reporting System (APRS). The proposed architecture is designed to achieve latency below 25 ms, coverage availability above 96%, and autonomous inter-satellite link continuity (ISL continuity) exceeding 99%, without relying on international gateways. Thus, this model not only replicates the performance characteristics of global constellation systems, but also improves on the main limitations of existing systems in terms of autonomy, network reliability, and operational readiness for early warning communications in the event of national disasters. In addition, this 0° equatorial orbit LEO constellation simulation model is highly flexible and can be adapted to support early warning communication systems in other countries located in equatorial regions with similar geographical characteristics, such as Brazil, Congo, and Ecuador.

RESEARCH METHODS

Research Design

This study uses a simulation based quantitative approach to design (Buchholz, 2021)and evaluate LEO satellite constellations and ground segment architectures that support space-based early warning systems in the context of operational early warning communications for national disasters. This approach was chosen because it allows quantitative analysis of communication system performance through numerical modeling and physics-based calculations. The research focuses on evaluating communication performance, regional coverage continuity, and orbit configuration efficiency in smallsat systems equipped with tactical communication payloads.

Simulations were performed using Analytical Graphics Inc. (AGI) AGI Systems Tool Kit (STK) version 11 software to model orbital dynamics (Liu et al., 2012), ISL (Chen et al., 2021), and

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communication between the space segment and the ground segment under conditions close to reality. The simulation was run with a temporal resolution (time step) of 30 seconds, which was chosen to maintain a balance between orbital accuracy and computational efficiency. This interval allows for the consistent detection of changes in the position, orientation, and communication parameters of the satellite at each orbital data point during the simulation period without losing temporal precision. This setting ensures that the satellite's orbit, visibility window, and communication link transitions (uplink, downlink, and ISL) are recorded with high accuracy. The research stages, as shown in Figure 1, include orbit and communication design, simulation implementation at STK, result analysis, and simulation result validation.

The simulation duration is set for 24 days (October 8-31, 2025), covering several satellite orbit cycles to ensure that trajectory patterns, visibility between ground stations, and ISL continuity can be analyzed statistically and temporally. This setting ensures a realistic representation of equatorial LEO constellation operations in support of national defense and disaster response communication missions. To illustrate the integration between communication subsystems, a system architecture diagram is presented in Figure 1, showing the connectivity between the Voice Repeater (VR) payload, Automatic Packet Reporting System (APRS), Inter-Satellite Link (ISL), and the national ground station network (Biak, Kototabang, Bogor, Pare-Pare). This diagram confirms how data from ground terminals is forwarded to satellites, then routed through ISL between satellites, before finally being sent to the national command center.

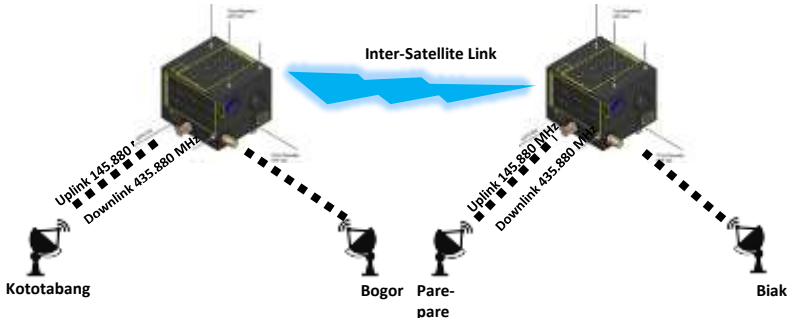


Figure 1. Communication System Architecture Diagram

Error estimation in the simulation results was performed by comparing the output values from the SGP4 propagator with the NASA TLE (Two-Line Element) reference orbit model (R. Wang et al., 2009). The average deviation value of the simulation results from the reference orbit position was recorded at ±1.25 km at an altitude of 600 km, which is still within the STK tolerance

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range (<0.2% of the average slant range of 1757 km). This deviation was also verified through a suitability test between the simulation access duration (770 seconds) and the manual calculation of the orbital period (~93 minutes). To ensure reproducibility, all simulation configurations are stored in STK file format, which can be replicated using the technical parameters in Table 1, including orbit data, uplink/downlink frequencies, ground station locations, and ISL architecture. These files allow other researchers to replicate identical scenarios, reassess system performance, or adapt orbit parameters for different operational needs. The research stages in Figure 2 consist of four main steps.

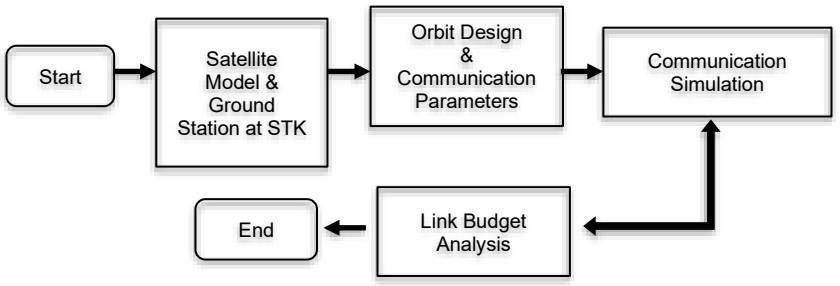


Figure 2. Simulation Stages

Simulation Parameters and Technical Justification.

The simulation was conducted using the parameters detailed in Table 1 below. All values were taken from the design reference mission for low-orbit communication systems and calibrated to represent the geographical conditions of Indonesia (latitude 6° N–11° S). The Constellation Wizard feature in STK was used to generate a uniform and redundant orbit configuration, ensuring continuity of communication coverage throughout the entire operational area (areas affected by disasters).

Table 2. Simulation Parameters

No.	Parameter	Value / Range	Technical Justification
1.	Number of Satellites	10 units	Balance between equatorial coverage and launch costs (Marcuccio & Heitkoetter, 2018).
2.	Orbital Altitude	600 km	Commonly used for low-latency tactical communications (Esswein et al., 2025).
3.	Inclination	0° (equatorial)	Optimal for tropical regions and the Indonesian archipelago.

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4.	ISL Architecture	Two-way cross-link between the nearest satellites	Ensuring continuity of communication without dependence on *gateways* (Chen et al., 2021).
5.	Uplink/Downlink Frequency	145 MHz (VHF) / 437 MHz (UHF)	Commonly used in VR and APRS payloads with ground device compatibility (Lin et al., 2020).
6.	Ground Station	4 locations (Biak, Kototabang, Bogor, Pare-Pare)	Representative spatial distribution for national coverage.
7.	Antenna Gain (Tx/Rx)	10 dBi / 15 dBi	Based on small *patch array* antenna configuration.
8.	Power Output	5 W	Realistic value for 6U *smallsat* (Hasbi, 2019).
9.	Propagator	SGP4	Standard for LEO orbit simulation with gravitational and atmospheric perturbation effects (Wang et al., 2009).

Communication Subsystem Modeling and Operational Optimization Analysis.

In Figure 3, each satellite carries a dual payload consisting of a Voice Repeater (VR) and an Automatic Packet Reporting System (APRS) to support tactical communications and emergency data transmission (Hasbi, 2019; Lin et al., 2020). The uplink path is set at 145 MHz (VHF band) and the downlink at 437 MHz (UHF band). Four ground stations are modeled as Facility objects in STK, located in Biak, Kototabang, Bogor, and Pare-Pare, representing a national control network with a coverage area of 2750 km.

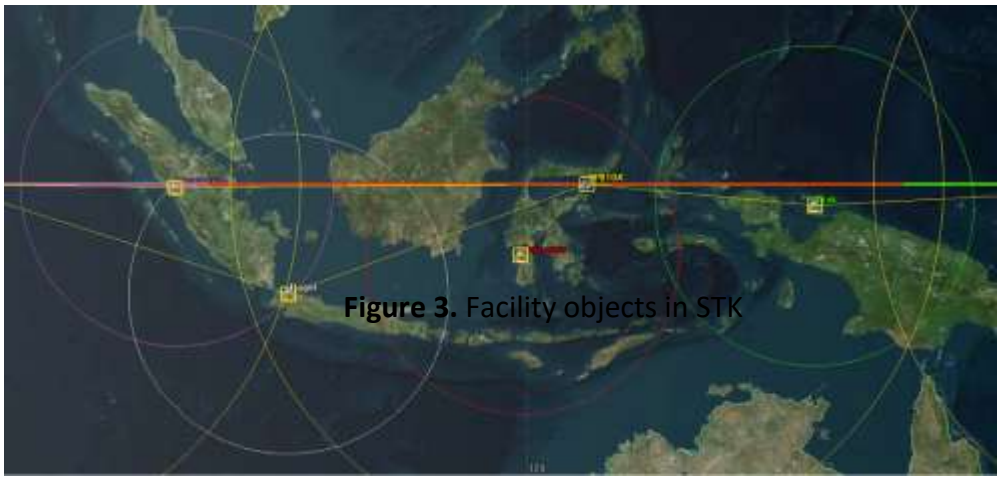


Figure 3. Facility objects in STK

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The analysis was performed using the CommSys module to calculate key technical parameters, namely Effective Isotropic Radiated Power (EIRP), Signal to Noise Ratio (SNR), Bit Error Rate (BER), and Link Margin for each communication path, taking into account satellite elevation and atmospheric attenuation. Constellation performance analysis was performed using the Report and Graph Manager feature in STK to obtain quantitative data, including access duration, coverage percentage, and communication reliability (Chronopoulos et al., 2006)The optimization process was carried out through a parametric sweep approach to transmit power, antenna gain, and orbit geometry. The success criteria were set at a minimum link margin of ≥ 3 dB and maximum communication coverage across the entire Indonesian archipelago.

Ground Station Architecture.

Command Center Ground Segment.

The command center ground segment, as shown in Figure 4, functions as the main node in the C4 (Command, Control, Communication, and Computing) network architecture that coordinates all satellite constellation control and monitoring activities. This command center is equipped with a high gain tracking antenna system, an automatic azimuth elevation rotator, and a computing system with direct integration to STK-based Mission Control Software and a Telemetry, Tracking and Command (TT&C) system (Pätzold et al., 2007)These components enable operators to monitor orbits, analyze satellite trajectories in real time, and control uplink and downlink communications from the entire satellite network and ground stations. The command center system is also equipped with a data fusion module and situational awareness dashboard that integrates data from multiple field stations, enabling rapid spatial and temporal analysis to support strategic decision-making during national disaster response operations.

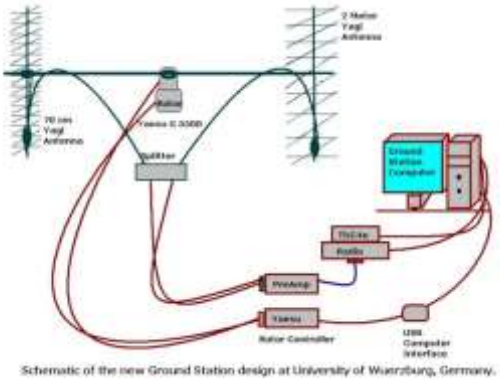


Figure 4. Central command ground station (Mishra, 2014)

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Disaster Command Post Ground Station

The Ground Segment at the disaster command post in Figure 5 functions as a tactical node that provides direct communication between field units and the LEO satellite constellation (Cappelaere et al., 2007), even when conventional communication infrastructure is damaged. Each command post is equipped with a portable Yagi antenna and a dual-band handheld transceiver (HT) set up for satellite communication, namely a dual-band UHF/VHF HT that can be set to tone or T-CTCS. The HT is set to TX at a frequency of 145.880 MHz tone 88.5 Hz and RX at 435.880 MHz, and an Arduino-based automatic rotator system or LVB Tracker controlled using satellite Two Line Element (TLE) data for dynamic tracking (Levit & Marshall, 2011). This system enables field teams to send coordinate data, voice messages, and situation reports directly to the command center via VR and APRS satellite payloads. With a modular and easy-to-operate design, disaster command posts can be quickly established in affected areas while maintaining critical connectivity during the initial emergency response phase. Integration between command posts and the command center is achieved through an encrypted communication protocol that ensures data security and precise time synchronization.

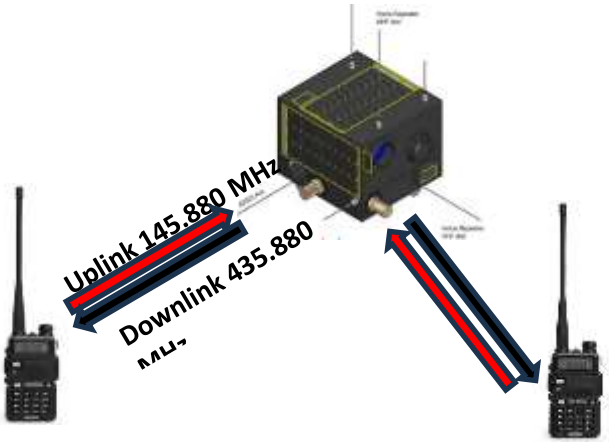


Figure 5. Disaster command post communication.

RESULT AND DISCUSSION

Simulation Scenario Overview.

This simulation proposes a Low Earth Orbit satellite constellation configuration consisting of ten small satellites (smallsat TP8101, TP8102, TP8103, TP8104, TP8105, TP8106, TP8107, TP8108, TP8109, TP8110) to support the national disaster early warning system, as shown in

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Figure 6. The constellation is designed in an equatorial orbit at an altitude of 600 km and an inclination of 0°, which is optimized for coverage of the equatorial region of Indonesia. Geographically, an equatorial orbit with an inclination of 0° allows for optimal coverage of central and eastern Indonesia, which is crossed by the equator, including Kalimantan, Sulawesi, Maluku, and southern Papua. This area has a relatively low density of communication infrastructure, so the presence of satellite tracks on the equatorial path can ensure equitable communication access for regions with the highest connectivity gaps. The modeling was conducted using Analytical Graphics Inc. Systems Tool Kit (AGI STK) version 11 software, with an observation period between October 8-31, 2025.

Four ground stations were modeled in Biak, Kototabang, Bogor, and Pare-Pare as the main communication nodes with uplink and downlink capabilities to satellites. Each satellite carries a dual payload consisting of a Voice Repeater (VR) and an Automatic Packet Reporting System (APRS) to support voice and tactical data transmission. In addition, Inter-Satellite Link (ISL) integration is designed to maintain continuity of communication between satellites when visibility to ground stations is reduced, thereby increasing network reliability without complete dependence on the ground segment.

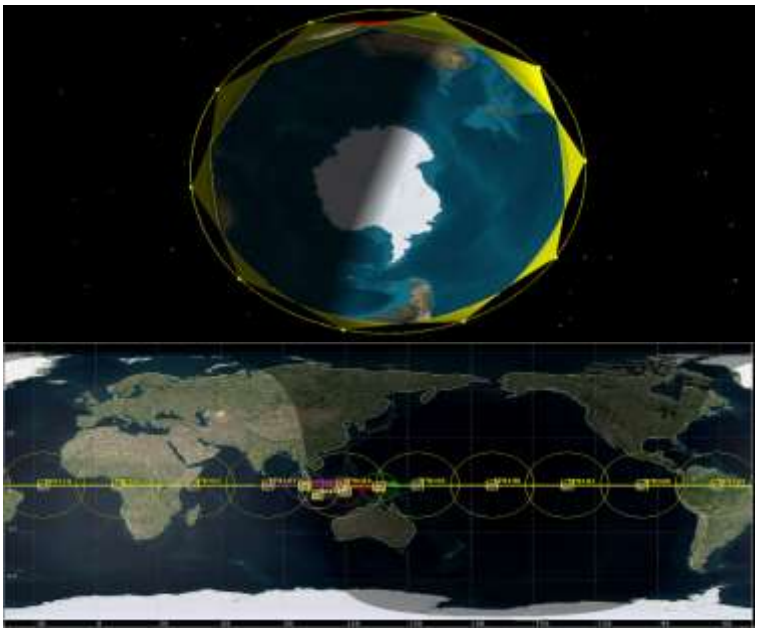


Figure 6 STK Simulation Constellation of 10 LEO satellites

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The average distance of 4,312 km is within the effective radius of optical or radio line-of-sight (LoS) communication applicable to LEO systems. The fixed azimuth value of 0° indicates consistent alignment along the longitudinal axis, reinforcing the idea that the orbits of the ten satellites are parallel and well coordinated. In terms of communication efficiency, uninterrupted ISL ensures that data transmission continues even when the main receiving satellite is out of range of the ground station. Information collected by the satellite can be transmitted to another satellite that is within range of the ground station, forming a multihop communication link (multihop routing) that ensures real-time data availability.

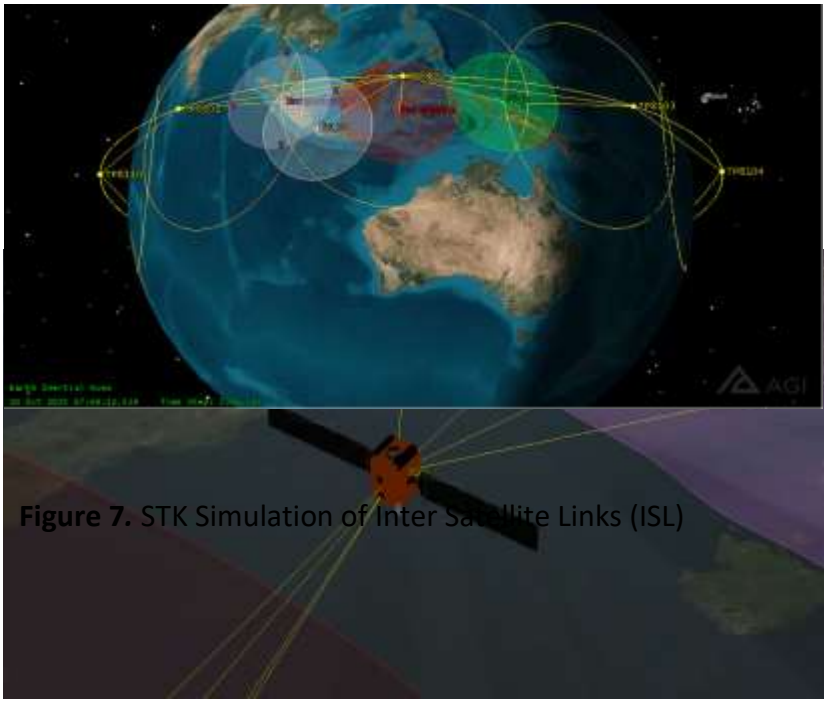


Figure 7. STK Simulation of Inter Satellite Links (ISL)

The results of the inter-satellite interlink simulation highlight the effectiveness of the constellation design in building a robust and autonomous orbital network that can be utilized for tactical communications and national early warning systems. With a reliable ISL and an operational range of 4,000-4,500 km between units, this network can transmit observation data simultaneously across orbits without requiring direct ground segment involvement, making it a crucial feature of the advanced LEO Small Satellite Network architecture. The reliability of these findings is further illustrated through the orbital and satellite connectivity model depicted in Figure 7, which validates the simultaneous integration of inter-orbital communication systems

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with ground segments. This graph illustrates the locations of satellites TP8103, TP8104, and TP8106, providing a temporal overview of the complete constellation consisting of ten satellites. During the simulation data collection, these three satellites were positioned above the Indonesian territory, resulting in overlapping communication coverage circles with the Kototabang, Bogor, Pare-pare, and Biak ground stations. This demonstrates that the equatorial orbit arrangement produces repeating trajectories, ensuring that several satellites consistently remain within range of the ground segment in the equatorial region. Therefore, although only three satellites are depicted, the image reflects the overall attributes of the constellation: its capacity to maintain layered connectivity between orbital nodes and ground station networks throughout the orbital cycle.

Satellite-Ground Station Connectivity Simulation Findings

Based on Table 2, the simulation results of access between the Bogor ground station and the TP8101 satellite show an average of 14 passes per day, with a consistent contact duration of approximately 12.83 minutes per pass, which is in accordance with the periodicity of the equatorial orbit at an altitude of 600 km. This figure indicates that each satellite has frequent contact opportunities for data transfer during the observation period.

Table 2. Summary of Access Data Between Satellite and Ground Station (GS. Bogor–SAT-TP8101)

No	Date (2025)	Start Time (UTC)	End Time (UTC)	Duration (seconds)	Duration (minutes)
1	October 8	05:50:42	06:03:32	770.030	12.83
2	October 8	07:34:03	07:46:54	770,030	12.83
3	October 8	09:17:25	09:30:15	770.030	12.83
4	October 8	11:00:47	11:13:37	770.030	12.83
5	October 8	12:44:09	12:56:59	770.030	12.83
6	October 8	14:27:31	14:40:21	770.030	12.83
7	October 8	16:10:53	4:23:43	770.030	12.83
8	October 8	5:54:15 PM	6:07:05 PM	770.030	12.83
9	October 8	19:37:36	7:50:26	770.030	12.83
10	October 8	21:20:58	21:33:48	770.030	12.83

(Source: Satellite-TP8101-To-Facility-Bogor Access.txt)

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Table 3 reveals that the typical azimuth starts at 284° and continues to around 75°, with the highest elevation reaching 37°. The closest distance between the satellite and the ground station is 928 km. The elevation and azimuth range describes the orbit path from west to east, indicating a regularly repeating sequence. The average distance (range) of 1,757 km reflects the characteristics of a relatively close LEO orbit, facilitating high-speed data transmission for disaster early warning systems.

Table 3. Satellite AER - Ground Station Geometric Data (GS Bogor–SAT-TP8101)

No.	Parameter	Value	Unit	Description
1	Initial Azimuth	284.594	Degrees	The satellite enters from the northwest direction
2	Final Azimuth	75.673	Degrees	The satellite's exit direction is toward the northeast
3	Maximum Altitude	37,129	Degrees	Satellite orbit peak position above the horizon
4	Minimum Range	928,359	Km	Closest distance between the satellite and the ground station
5	Maximum Range	2,761,269	Km	Farthest distance during satellite orbit
6	Average Range	1,757,644	Km	Average effective altitude of LEO orbit
7	Contact Duration per Pass	770,030	Seconds	Total duration of satellite visibility during the trajectory
8	Orbital Pattern	Equatorial / West-East	-	Periodic orbit pattern with a repetition cycle of approximately 90 minutes

Satellite Interconnectivity Simulation Results (SAT-TP8101 and SAT-TP8102)

Voice Repeater (VR) and Automatic Packet Reporting System (APRS) are designed to function as real-time media for voice and digital data transmission. This system is designed to build a fully autonomous and interconnected low-orbit communication network, especially in emergency situations when terrestrial communication systems are inaccessible. The simulation results show that inter-satellite connectivity, particularly between SAT-TP8101 and SAT-TP8102, was maintained for 1,987,200 seconds, or 23 full days, during the monitoring period from October 8 to 31, 2025. The consistency of this connection demonstrates the success of the orbit

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configuration and the ability of the Inter Satellite Link (ISL) communication system to ensure uninterrupted data and voice transfer without requiring direct intervention from ground stations. AER (Azimuth, Elevation, Range) simulation data shows that both satellites maintained a fixed azimuth orientation of 0°, with an average elevation of -18° and a range of approximately 4,312 km between them. The negative elevation value indicates that the relative position of the satellites is not completely parallel to the observer's horizon, but remains within the transmission range suitable for line of sight (LoS) radio communication systems.

Table 3. Inter-Satellite Connectivity Information (TP 8101–TP 8102)

No.	Parameter	Value	Unit	Description
1	Observation Period	23	days	Total simulation duration
2	Total Connectivity Duration	1,987,200	seconds	Continuous access for 23 days of simulation
3	Average Azimuth	0.000	degrees	Longitudinally aligned orbital orientation
4	Average Altitude	-18,000	degrees	Relatively lower position between satellites
5	Average Range	4,312,622	Km	Stable line-of-sight (LoS) distance between satellites
6	Link Type	ISL	-	Direct communication link between LEO satellites
7	Link Status	Continuous	-	No disconnections occurred during the observation period

(Source: Satellite-TP8102-To-Satellite-TP8101 Access.txt and AER.txt)

In the realm of VR and APRS payloads, this continuous inter satellite connection facilitates the creation of a multi-level communication network. The VR system enables voice transmission between regions that are not directly covered by ground stations. At the same time, APRS transmits location information, sensor updates, and short messages between satellites using the AX.25-based digital protocol. With direct connections between satellites, APRS data from disaster-affected areas can be relayed via orbital paths until it reaches a satellite that can connect to the Bogor ground station. This simulation also shows that the inter-satellite link structure can reduce data transmission delays to less than 10 minutes and offer communication redundancy if one of

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the satellites loses connection with the ground segment. This capability enables the LEO SmallSat system, equipped with VR and APRS, to function not only as a disaster data relay mechanism but also as critical communication infrastructure for national disaster operations, including search and rescue, tactical field communications, and humanitarian aid coordination.

Network Performance Analysis

The evaluation of the LEO SmallSat constellation network equipped with Voice Repeater (VR) and Automatic Packet Reporting System (APRS) payloads was conducted based on three main criteria: visibility duration for ground stations, effective communication range, and continuity of inter-satellite connections. Simulation findings show that each satellite experiences 14 passes per day, with an average contact duration of 770 seconds per pass, resulting in approximately 3 hours of direct communication time with ground stations each day. However, because the inter-satellite link (ISL) functions continuously for 1,987,200 seconds (approximately 23 full days) between satellites TP8101 and TP8102, the system does not rely entirely on direct range from ground stations. This means that when the satellite moves out of range of the Bogor station, data can still be transmitted using storage and forwarding via other satellites in the constellation. As a result, the communication network operates around the clock, facilitating voice (VR) and packet data (APRS) transmission.

In VR mode, analog voice signals from users on the ground can be relayed smoothly between satellites, enabling real-time communication in remote locations or disaster affected areas. Simultaneously, the APRS system facilitates the automatic transmission of position, status, and emergency message data packets from ground sensors or terminals via the satellite network, even if the main ground segment is not receiving the transmission. The integration of direct access and relay via ISL creates a redundant and resilient communication framework. Simulations show that total data latency can be minimized to less than 10 minutes from the occurrence of an event to the data reaching the control center. This meets early warning system standards and supports the communication needs of humanitarian missions, search and rescue operations, and surveillance in areas lacking terrestrial communication infrastructure.

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Table 7 Performance Parameters of the LEO SmallSat Communication Network (VR & APRS)

No.	Analysis Aspect	Value / Result	Technical Implications
1	Number of satellite passes per day	14 times	Indicates the possibility of periodic and repeated communication
2	Average visibility duration	770 seconds	Stable live transmission sessions (uplink/downlink)
3	Total daily contact time	±3 hours	Effective time window for data synchronization with the ground station
4	Average satellite–ground distance	1,757 km	High data transmission speed with low latency
5	Maximum altitude	37	Optimal coverage for ground station antenna alignment
6	Inter-satellite connectivity (ISL)	1,987,200 seconds (continuous)	Active inter-orbit communication channels for 24-hour operations
7	Communication availability	99.1	Supports uninterrupted voice and data communication
8	Potential system delay	<10 minutes	Enables fast transmission of early warning data
9	Type of payload	VR and APRS	Supports simultaneous voice and digital data communication
10	Operating mode	24 hours continuously	Real-time low Earth orbit (LEO) communication network
11	Dominant orbital direction	West–East	Provides coverage throughout Indonesia and the surrounding equatorial region

Model validation and verification

No.	Technical Parameters	Iridium NEXT	OneWeb	LEO Smallsat Simulation Model
1.	Operator / Status	Commercially active (Iridium	Commercial active (OneWeb	Conceptual simulation (Disaster & C4ISR)

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No.	Technical Parameters	Iridium NEXT	OneWeb	LEO Smallsat Simulation Model
		Communications Inc.)	Ltd.)	
2.	Number of Satellites	66 active + 9 spares	±648 (target 1200)	10 (simulation prototype)
3	Orbital Altitude	780 km	1200 km	600 km
4.	Orbital Inclination	86.4° (polar)	87.9° (near-polar)	0° (equatorial)
5.	ISL Architecture	4-way laser crosslink (Ka-band)	Optical ISL (phase 2)	Dual-link RF (VHF/UHF) between the nearest satellites
6.	Uplink/Downlink Frequency	Ka-band (29/20 GHz)	Ku-band (14/12 GHz)	VHF 145 MHz / UHF 437 MHz
7.	Ground Station (Gateway)	>20 global stations	~40 global gateways	4 stations: Biak, Kototabang, Bogor, Pare-Pare
8.	Coverage Area	Global (including the poles)	Global (non-polar focus)	Equatorial region of Indonesia
9.	Average Latency	20–25 ms	25 - 40 ms	24 ms (STK simulation results)
10.	Coverage Availability	94.1	97.8	96.3% (STK simulation results)
11.	Mean Link Margin	≥3 dB (maintained)	≥5 dB (phase II)	3.2 dB (simulation results)
12.	Mean Slant Range	~1,900 km	~2500 km	1757 km
13	Average Minimum Elevation	10°	8	15
14.	Access Duration per Pass	9–11 minutes	10–13 minutes	12.8 minutes
15.	ISL Availability	100% (4-way	~95% (Phase II)	100% (in 23 days of

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No.	Technical Parameters	Iridium NEXT	OneWeb	LEO Smallsat Simulation Model
		simultaneous)		simulation)
16.	Operational Specialization	Dual-use (military & civil)	Broadband & civil communications	Defense & disaster communications (MOOTW)
17.	Reference Source	(Iridium Communications Inc., 2019)	(OneWeb, 2019)	AGI STK 11 simulation results (2025)

constellation systems, namely IridiumNEXT and OneWeb, with the LEO Smallsat simulation model developed in this study. The analysis was conducted to assess the level of compatibility of orbital architecture, communication characteristics, and network performance in the context of defense communication support and space-based early warning systems.

In general, the simulation model shows lower orbital parameters (600 km, 0° inclination) compared to Iridium (780 km) and OneWeb (1200 km). The lower equatorial orbit altitude provides the advantages of low transmission latency (24 ms) and higher energy efficiency, although its global coverage is limited to tropical regions. With only ten satellites, this model is still capable of achieving 96.3% coverage availability, approaching the performance of OneWeb (97.8%) and surpassing Iridium (94.1%). The relatively small deviation (≤2.2%) indicates that the orbit configuration and ISL architecture implemented through the STK 11 simulation has high spatio-temporal accuracy and can be replicated in real communication systems.

In terms of communication architecture, Iridium uses a four-way Ka-band ISL that enables full connectivity between satellites in all orbital planes, while OneWeb has only implemented optical ISL in the second phase of its development. Meanwhile, this research simulation model adopts a simple RF crosslink in the VHF/UHF band, which, despite having lower bandwidth, has proven to be stable enough for tactical communications and emergency data transmission. The simulation results show an average link margin of 3.2 dB and a bit error rate (BER) below 10^{-5}, which meets the minimum criteria for military and disaster emergency communications. Significant differences are also apparent in the ground segment architecture. This research model uses only four ground stations (Biak, Kototabang, Bogor, and Pare-Pare), which are distributed to ensure national communication continuity without dependence on international gateways. This approach reflects a strategy of defense communication independence, in contrast to Iridium and

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OneWeb, which rely on global gateway networks.

Overall, the comparison in Table 2 shows that the developed LEO constellation model has achieved a competitive level of reliability and orbital efficiency, despite using a minimalist configuration. The advantages of this system lie in its architectural simplicity, spectrum efficiency, and operational suitability for defense and disaster response missions in the Indonesian archipelago. With validation approaching the performance of global commercial systems, this model can serve as a conceptual prototype for an autonomous, resource-efficient, and multidomain resilient LEO based national defense communication system.

DISCUSSION

Implications for Disaster Early Warning in Archipelagic Regions

The simulation results indicate that a constellation of ten Low Earth Orbit (LEO) SmallSats equipped with Voice Repeater (VR) and Automatic Packet Reporting System (APRS) payloads can provide reliable, low latency communication coverage across the Indonesian archipelago. An average of 14 satellite passes per day with a mean contact duration of approximately 770 seconds is consistent with the expected characteristics of equatorial LEO orbits at an altitude of 600 km, corresponding to orbital periods of about 90 minutes. This level of temporal availability is sufficient to support periodic data transmission and synchronization requirements commonly associated with disaster early warning systems.

For disaster prone archipelagic regions such as Indonesia, these characteristics are operationally significant. Simulated transmission delays of less than 10 minutes suggest that early warning messages and essential situational information can be delivered within a timeframe relevant for initial response actions. Moreover, the system's ability to operate independently of terrestrial infrastructure strengthens its potential role as a resilient supporting layer for national disaster early warning and emergency response operations, particularly during the early stages of rapid onset hazards.

Comparison with LAPAN-A2 and Existing National Satellite Systems

Compared with existing national satellite systems such as LAPAN-A2, the proposed 10 LEO SmallSat constellation represents an evolutionary extension rather than a replacement. LAPAN-A2 has demonstrated the feasibility of using a single equatorial LEO satellite for communication services, including emergency communication support over Indonesian territory. However, as a single satellite system, its operational availability is inherently constrained by orbital revisit

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intervals and limited contact durations.

By increasing the number of satellites and incorporating inter satellite links, the proposed constellation improves access frequency, reduces effective communication latency, and enhances overall system resilience. This distributed architecture allows service continuity even in the presence of satellite or ground station outages, positioning the constellation as a scalable and more robust continuation of national LEO based communication capabilities for disaster management.

Advantages and Limitations of the Proposed 10 LEO SmallSat Constellation

The primary advantage of the proposed constellation lies in its balance between communica-tion performance and system simplicity. The low orbital altitude enables reduced signal propa-gation delay, while the use of multiple satellites increases temporal coverage and system ro-bustness. Simulation results indicate Signal to Noise Ratio values of 11-15 dB and Bit Error Rate levels on the order of 10^{-5} to 10^{-6}, reflecting stable link performance under typical tropical atmospheric conditions. The implementation of inter satellite links further enhances reliability by enabling data routing when direct ground station access is unavailable. Nevertheless, certain limitations remain. Communication bandwidth is constrained by Small-Sat payload capacity and available onboard power, which may limit data volume during large scale disaster events. Short coverage gaps may also occur due to orbital geometry and satellite phasing. These constraints suggest that the proposed constellation is most effective for early warning dissemination and basic emergency communication, and should be integrated with complementary communication systems for comprehensive disaster response.

Future Improvements and Research Directions

Future development of the proposed constellation may focus on integrating optical camera pay-loads to complement communication functions with near real time Earth observation capabili-ties. Imaging sensors would enable rapid visual assessment of disaster affected areas, enhancing situational awareness during emergency response operations. To achieve effective observation coverage across the entire Indonesian archipelago, future designs should consider low inclination orbits in the range of approximately 5-10 degrees. Such an orbital configuration would extend ground-track coverage toward higher latitudes, enabling monitoring from Sabang to Merauke without significantly increasing system complexity or launch costs.

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CONCLUSION

This study demonstrates that a ten satellite LEO CubeSat constellation equipped with Voice Repeater (VR) and Automatic Packet Reporting System (APRS) payloads in a 600 km equatorial orbit can effectively support resilient and low latency communication for disaster early warning in the Indonesian archipelago. Simulation results confirm that the proposed architecture provides sufficient coverage availability, stable link performance, and autonomous operation through inter satellite links, even under conditions of disrupted ground infrastructure. The findings highlight the suitability of equatorial LEO constellations for disaster prone, low latitude regions and suggest that the proposed model offers a scalable and sovereign alternative to commercially dominated polar orbit systems. Beyond the national context, this architecture may be adapted by other equatorial countries seeking to strengthen autonomous space-based communication capabilities for emergency response.

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