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Optimal Orbital Inclination Based on Maximum Regional Coverage Criterion for A Satellite in A Low Earth Circular Orbit

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ABSTRACT

Considering the growing range of space applications, missions targeting regional coverage have become increasingly significant. This study presents two analytical algorithms to determine the optimal orbital inclination for maximizing regional coverage for a satellite in a low Earth circular orbit. Specifically, the algorithms utilize a two-dimensional mapping technique and geographic latitude-dependent coverage calculations to derive optimal orbital parameters. For instance, for a satellite at an altitude of 700 kilometers with a minimum elevation angle of 20 degrees (corresponding to a field of view of 115.6 degrees), the optimal orbital inclination for maximizing coverage over Iran's target region is found to be 39 degrees using both analytical methods. These findings are validated through simulations conducted in STK software, which reveal an accuracy error of 5% or less. By filling gaps in the existing literature with its focus on regional coverage for micro-satellites, this study advances the understanding of regional mission planning and provides satellite designers with efficient and practical tools for optimizing orbital parameters. The proposed algorithms hold promise for diverse applications, including disaster monitoring and communication satellite design.

1 INTRODUCTION

The design and deployment of satellite constellations in Low Earth Orbit (LEO) have become a cornerstone of modern aerospace engineering, driven by the increasing demand for enhanced communication, navigation, and Earth observation services. Optimal geometric coverage in LEO is critical for applications ranging from regional disaster monitoring to the Internet of Things (IoT) and global connectivity. However, achieving efficient regional coverage with a limited number of satellites presents significant challenges, including balancing revisit time, ground track periodicity, and operational constraints such as limited propulsion and onboard power systems [1, 2]. This study aims to address these challenges by proposing novel methods for designing satellite constellations optimized for regional coverage missions.

Traditional approaches to satellite constellation design have focused on global coverage. Geostationary and geosynchronous orbits are frequently used for regional missions, offering continuous coverage of specific areas with minimal satellite numbers [3]. However, advancements in

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LEO satellite technologies, including reduced launch costs and miniaturized payloads, have shifted the focus to constellations in LEO, which offer shorter signal latencies and lower transmission power requirements [4, 5]. Despite these advantages, LEO satellites have inherently smaller instantaneous coverage areas, necessitating innovative approaches to constellation design to achieve regional coverage efficiently. Moreover, the dynamic nature of LEO orbits introduces additional challenges, such as managing orbital decay and maintaining periodic ground tracks [6].

Several methodologies have been developed to optimize satellite constellations for regional missions. Hanson et al. [2] demonstrated that constellations with repeating ground tracks provide shorter revisit times, making them suitable for regional applications. Ulybyshev [3] proposed the Delta-Walker constellation pattern for regional coverage, introducing a robust framework for complex geometric designs. Metaheuristic algorithms, such as genetic algorithms and ant colony optimization, have also been employed for constellation design [4, 7, 22]. For instance, Zhang et al. [5] and Kim et al. [7] used genetic algorithms to optimize regional coverage in specific geographic regions, including China and the Korean peninsula.

Sparse satellite constellations represent a promising solution to the challenges of regional coverage in LEO. Capez et al. [15] demonstrated that sparse constellations can achieve efficient regional and global IoT coverage with fewer satellites, significantly reducing deployment and operational costs. These constellations leverage advanced communication protocols, such as beam-hopping and dynamic resource allocation, to maximize coverage flexibility [16, 23]. Moreover, reconfigurable constellations, which adapt to evolving mission requirements, have gained traction in disaster monitoring and IoT applications [22, 25]. For example, Fischer and Guo [23] optimized sparse IoT satellite constellations for cost and coverage trade-offs, while Melaku and Kim [22] developed a multi-objective genetic algorithm for CubeSat constellations.

This research contributes to the existing literature by presenting a novel analytical framework for designing satellite constellations optimized for regional coverage in LEO. Unlike traditional methods that rely on computationally intensive simulations or metaheuristic algorithms, this study introduces two analytical algorithms that provide rapid and accurate solutions. The first algorithm leverages a two-dimensional mapping technique to determine the optimal orbital inclination for regional coverage, considering both satellite geometry and the target region's latitude [4, 5]. The second algorithm calculates coverage as a function of geographic latitude, enabling mission designers to evaluate coverage trade-offs without extensive dynamic simulations. These algorithms are validated through simulations using STK software, demonstrating their effectiveness and reliability under various mission scenarios.

Recent advancements in LEO satellite technologies and constellation design further underscore the importance of this research. For instance, Zhao and Zhang [26] explored the challenges of designing LEO constellations for IoT applications, highlighting the need for innovative coverage optimization techniques. Similarly, Okati and Riihonen [21] conducted a stochastic analysis of LEO constellations, providing valuable insights into coverage probabilities and data rates for regional missions. By integrating these state-of-the-art methodologies, this study bridges the gap between theoretical models and practical applications, offering a comprehensive solution for regional coverage missions in LEO.

The remainder of this paper is organized as follows: Section 2 introduces the first analytical algorithm for optimizing orbital inclination, with a case study focused on Iran's geographic region. Section 3 describes the second algorithm, which evaluates coverage as a function of latitude. Section 4 validates the proposed methodologies through STK simulations, and Section 5 concludes with a summary of findings and recommendations for future research.

2 FIRST ANALYTICAL METHOD FOR FINDING OPTIMAL ORBITAL INCLINATION BASED ON MAXIMUM REGIONAL COVERAGE

This section describes the algorithm for searching the optimal orbital inclination for a specified target region. This algorithm visualizes the observability of circular orbits without using dynamic simulations, considering the instantaneous coverage angle of the satellite (i.e., the payload's field of view) using the geometric relationship between the satellite and the specified ground region. Here, the two-dimensional coverage mapping, defined by Hanson in 1990 [2] and Ulybyshev in 2008 [3], is used to assign numerical values to the satellite's observability capability based on the area corresponding to its coverage diagra

2.1 Two-Dimensional Coverage Mapping

The two-dimensional mapping accepts a two-dimensional space consisting of the geographic latitude argument $u \epsilon [0^{\circ}, 360^{\circ}]$ and the ascending node angle $\Omega \epsilon [0^{\circ}, 360^{\circ}]$ as its domain. The coverage function $f(\Omega,u) \geq 0$ maps the Ω−u pairs to a positive real value if the specified ground target is observed, and to zero otherwise. To obtain the two-dimensional coverage map, the function fff is defined according to Equation (1). Figure 1 illustrates the geometric relationship of the function f. In Figure 1, the angle θ is measured from the sub-satellite point to the ground target, and the angle Ψ is measured from the sub-satellite point to the maximum instantaneous coverage boundary. Both angles are measured from the Earth's center. Using the ground-center latitude and longitude of the sub-satellite point $(\lambda_{sat},\phi_{sat})$ and the ground target $(\lambda_{tgt},\phi_{tgt})$, the angle θ can be calculated using the cosine law in spherical trigonometry as per Equation (2):

$$f(\Omega,u) = \begin{cases} 1\ ;\ \Psi - \theta(\Omega,u) \geq 0 \\ 0\ ;\ \Psi - \theta(\Omega,u) < 0 \end{cases} \quad (1)$$

$$\cos\theta = sin\varphi_{tgt} sin\varphi_{sat} + cos\varphi_{tgt} cos\varphi_{sat} \cos(\lambda_{tgt} - \lambda_{sat}) \quad (2)$$

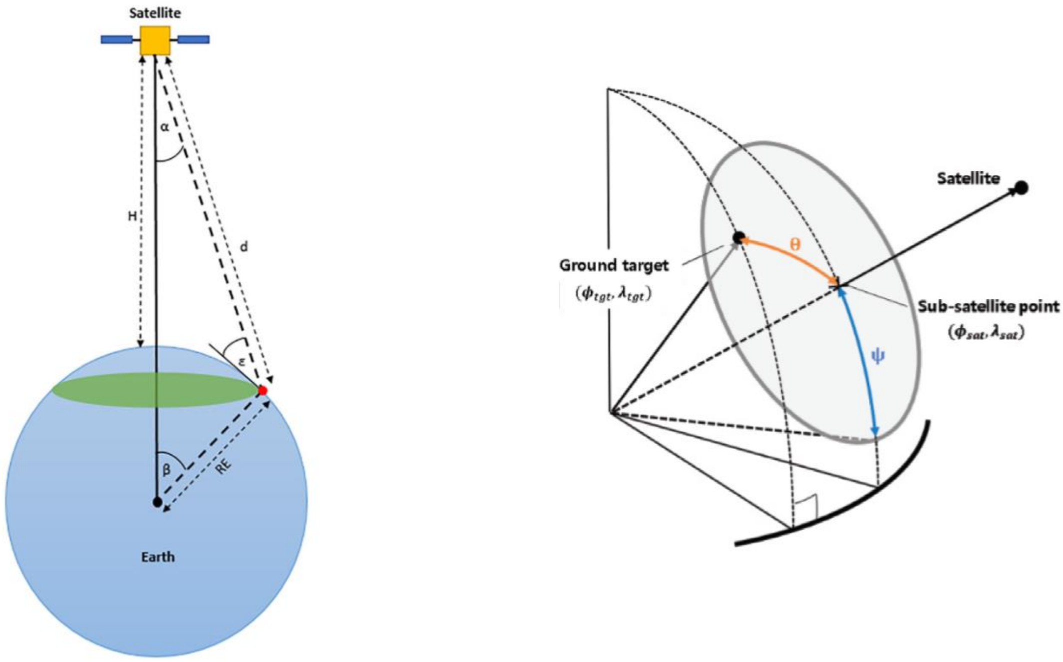


Figure 2. The geometric relationship between the sub-satellite point and the ground target.

Assuming α is the half-angle of the payload's field of view, the angle Ψ is calculated according to Equation (3) [13]. In Equation (3), R_E is the Earth's radius, and h is the orbital altitude.

$$\Psi = \frac{\pi}{2} - \alpha - \text{acos}\,(\frac{sin\alpha(R_E + h)}{R_E}) \quad (3)$$

Thus, the orbital observability capability can be mapped in a two-dimensional diagram. For example, Figure 2 shows the two-dimensional coverage mapping obtained by calculating the coverage function for a satellite in a circular orbit at an altitude of 700 kilometers with an orbital inclination of 39 degrees, considering Tehran as the ground target. In this example, the satellite's instantaneous coverage half-angle is assumed to be 60 degrees. In other words, Figure 2 illustrates the u−Ω pairs for a satellite in a circular orbit at 700 kilometers altitude and 39 degrees inclination that covers the Tehran target region.

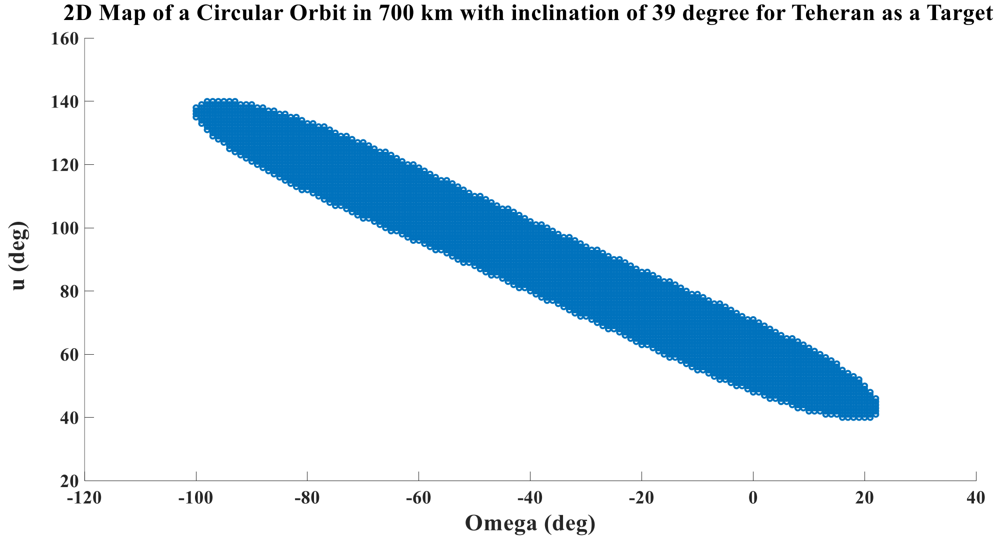


Figure 2. Two-dimensional coverage mapping diagram for a circular orbit at 700 kilometers Altitude and 39 Degrees inclination for Tehran.

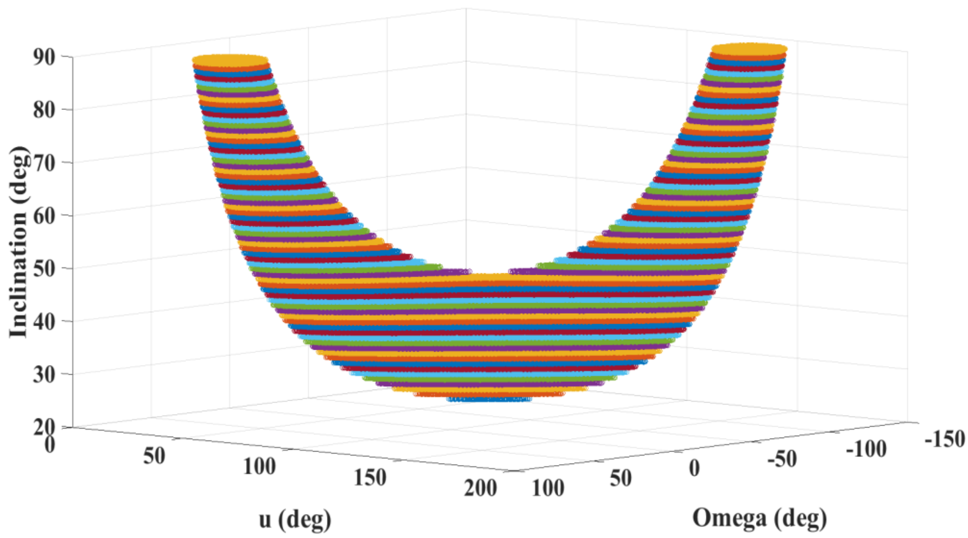
2.2 Coverage Mapping with Optimal Orbital Inclination

The optimal orbital inclination search algorithm in this method finds the inclination that maximizes the orbit's observability. Initially, it is assumed that the area of the two-dimensional map represents the orbit's observability capability and is defined as a function to be maximized. It should be noted that in circular orbits, the major axis, orbital inclination, ground target positions, and any other observability conditions, such as minimum elevation angle or payload field of view, must be specified. Therefore, given the ground target and the payload's field of view, the optimal inclination i^* for circular orbits is defined according to Equation (4):

$$i^* = argmax_i A(a,i) \quad (4)$$

In the two-dimensional mapping algorithm, the area of the two-dimensional map is calculated by summing the weighted areas within the selectable inclination range with a fixed resolution. In this study, for example, , the inclination range and resolution are set to 0 to 90 degrees and 0.1 degrees, respectively. Then, the inclination that maximizes this value is selected as the optimal orbital inclination.

Figure 3 is an example presented in a three-dimensional plot, showing a stack of two-dimensional maps across the selectable inclination range along the z-axis. This figure illustrates an optimal inclination where the cross-sectional area is maximized.



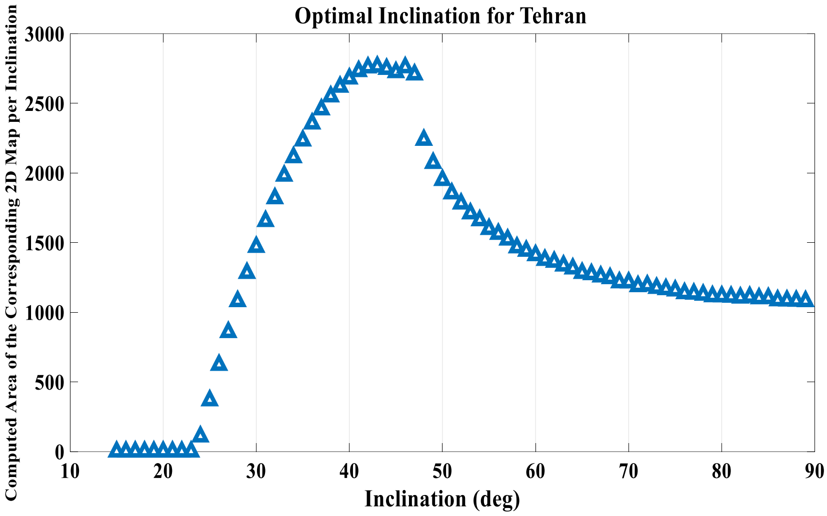


Figure 3. (a) Three-Dimensional Coverage Graph within the Selectable Inclination Range, (b) Two-Dimensional Map Area Corresponding to Each Orbital Inclination (for finding the optimal inclination for Tehran as the ground target).

This method can be used for regional coverage by considering the desired ground region as a set of discrete ground targets with specified latitudes and longitudes. When multiple ground targets are considered, the optimal inclination is defined as the one that maximizes the sum of the weighted areas of the two-dimensional maps. In Equation (5), A_k is the area of the two-dimensional map for the *k-th* ground target, w_k is its corresponding weight, and N_T is the total number of ground targets. Therefore, the two-dimensional map area becomes a function solely dependent on the orbital inclination.

$$i^* = argmax_i \sum_{i=1}^{N_T} A_k\,(a,i) w_k \qquad (5)$$

Table 1 provides the pseudocode for the two-dimensional mapping algorithm, and Figure 4 shows the optimal orbital inclination considering Iran's target region for a satellite in a circular orbit at 700 kilometers altitude with a minimum elevation angle of 20 degrees (corresponding to a field of view of 6/115 degrees). Here, the resolution for determining the set of ground targets in Iran's target region is assumed to be 0.5 degrees, thus considering 515 ground targets with specified latitudes and longitudes and uniformly distributed weights for the ground target set.

Table 1. Pseudocode for the Optimal Orbital Inclination Search Algorithm

Algorithm Inputs	Description
i_{min},i_{max}	Minimum and maximum inclination values
γ	Inclination step resolution within the search range
$A_l(i)$ $where\ i = 1, \ldots, N_T$	Two-dimensional map area for each grid (in a grid composed of a set of grids labeled with corresponding latitudes and longitudes in the target region)
W_l	The corresponding weight for each grid in the target region
N_T	Number of grids in the target area

Desired Algorithm Output: Optimal orbital inclination i^*	
oop for all possible orbital inclinations (within the range of minimum and maximum inclination values with an increment step γ).	$for\ i = i_{min}: \gamma: i_{max}$
alculate the area of the two-dimensional map corresponding to each grid and sum their weighted values.	$A_{wsum}(i) = \sum_{l=1}^{N} A_l(i) \times W_l$
tore the summed weighted areas for all grids at each inclination.	$save\ A_{wsum}(i)$
End Loop.	end
etermine the optimal orbital inclination for the target region.	$i^* = \underset{i}{\mathrm{argmax}} A_{wsum}(i)$

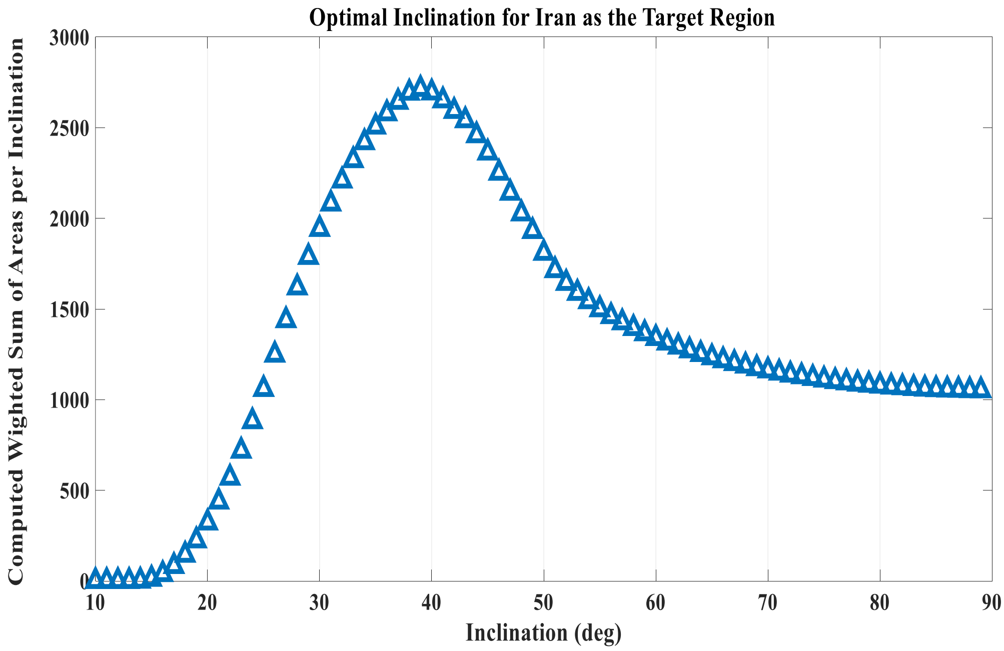


Figure 4. Optimal Orbital Inclination for Iran's Region Based on the Two-Dimensional Mapping Analytical Method.

3 SECOND ANALYTICAL METHOD FOR FINDING OPTIMAL ORBITAL INCLINATION BASED ON MAXIMUM REGIONAL COVERAGE

The second method is based on calculating coverage as a function of geographic latitude $\mathscr{L}$. A simple approach assumes a fixed and non-moving orbit (coverage pattern) with the Earth rotating beneath it, as shown in Figure 5. In Figure 5(a), the red circles indicate the position of the ground station or target in successive orbital passes. This image highlights the discrete nature of coverage and the extraction of a continuous analytical formula. If the coverage pattern's width (the area bounded by two dashed lines) is narrower than the distance between two consecutive red circles, there may be coverage gaps during ascending and descending passes. If the coverage pattern's width exceeds one distance (the distance between two consecutive red circles) but is less than two distances, coverage can occur in one pass or both ascending and descending passes. Therefore, the entire Earth can be divided into regions with specific geographic latitudes where each region has a discrete set of possible coverage patterns. To achieve a continuous analytical approximation, it must be considered that the arc length connecting small points is directly related to the coverage percentage at that geographic latitude. It is emphasized that coverage is not a statistical variable; for example, in a one-day repeating ground track orbit,, targets appear at the same location relative to the orbit daily, making coverage a function of longitude and latitude. In other words, each location on Earth's surface has its own fixed coverage pattern. If the orbit does not have a repeating ground track, the coverage percentage rule can be applied [14]. Specifically, it is assumed that the satellite is in a circular orbit with inclination iii, and observations, as shown in Figure 5(b), can be made at angles less than or equal to λ_{max} on both sides of the ground track. It is also assumed that L is positive,, meaning the target region is in the Northern Hemisphere (generalizable to the Southern Hemisphere or asymmetric observations [14]). As shown in Figure 5(b), depending on geographic latitude and orbital inclination, three coverage scenarios can exist: no coverage, a wide coverage area, or two smaller coverage areas.

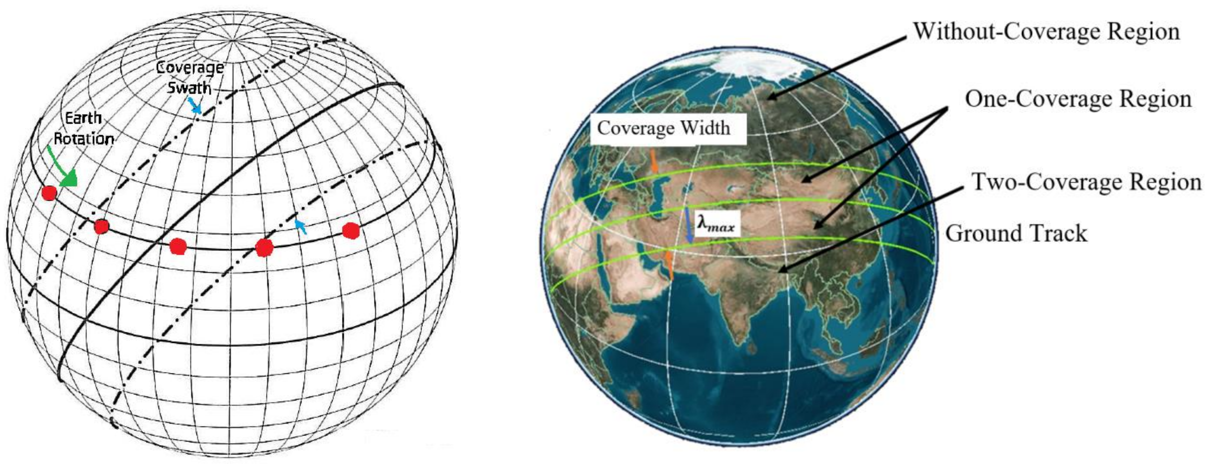


Figure 5. (a) Alternative representation of a rotating ground track, (b) different coverage scenarios.

Table 2. Coverage as a function of geographic latitude.

Geographic Latitude Region	Number of Coverage Areas	Coverage Percentage
$L > \lambda_{max} + i$	0	0
$i + \lambda_{max} > L > i - \lambda_{max}$	1	$\phi_1/180$
$i - \lambda_{max} > L > 0$	2	$(\phi_1 - \phi_2)/180$
$\cos\cos\phi_{1\ or\ 2} = \frac{\pm\sin\lambda_{max} + \cos i \sin L}{\sin i \cos L}$		

The mathematical relationship for coverage as a function of geographic latitude is presented in Table 2. In calculating the angle ϕ, a negative sign is assigned to ϕ_1 and a positive sign to ϕ_2. Here, ϕ represents half the range of geographic longitude where coverage occurs. The formula in the third column indicates the portion of all points at a specific geographic latitude that is within the satellite's visibility during an orbital pass. This roughly corresponds to the portion of orbits that cover a known point (at that geographic latitude). For example, consider a satellite at an altitude of 700 kilometers with an orbital inclination of 55 degrees and a minimum elevation angle of 20 degrees (maximum angle outside the ground track λ_{max} is 2/12 degrees). For the Tehran ground station at a geographic latitude of 7.35 degrees, the coverage percentage is 9.46%. In each orbital pass, 9.46% of points at a geographic latitude of 7.35 degrees will be within the satellite's field of view. Consequently, a point at a geographic latitude of 7.35 degrees will be covered in approximately 47% of the satellite's orbits. Since, in this example, , only one coverage area exists, orbital passes with coverage occur continuously throughout the day. Figure 6 shows the coverage curves for different geographic latitudes for a satellite at an altitude of 700 kilometers with an orbital inclination of 55 degrees and a minimum elevation angle of 20 degrees (maximum angle outside the ground track λ_{max} is 2/12 degrees). At geographic latitudes less than $i - \lambda$, there are two separate coverage areas. In this region, coverage increases with increasing latitude as the satellite's inclined orbit becomes more tilted away from the equator, thus providing more coverage at specific latitudes. At the geographic latitude $i - \lambda$, a transition occurs from areas with two coverage regions to a single, extensive coverage area. As seen in Figure 6, this region is where the geographic latitude line is tangent to the edge of the coverage band, representing the latitude with the maximum coverage. As geographic latitude increases beyond this threshold, coverage decreases because the single coverage area becomes smaller until coverage completely disappears at a geographic latitude of $i + \lambda$. From the curve in Figure 6, it can be concluded that coverage significantly depends on geographic latitude, and the orbital inclination can be designed to maximize coverage in the desired region.

Satellite coverage depends on the orbital inclination parameter [14]. Specifically, Figure 7 illustrates how a satellite in a circular orbit at 700 kilometers altitude with a minimum elevation angle of 20 degrees can provide coverage at different geographic latitudes with varying orbital inclinations. This information is used to limit the possible orbital inclination values to supply coverage for a set of points $\{\mathcal{L}\}$. For example, in a set $\{\mathcal{L}\}$ where all points $P \in \{(i,j)\}$ are at geographic latitudes less than 80 degrees, selecting an orbital inclination less than 60 degrees is ineffective and should be excluded from the search space (note that this relationship also depends on the payload's field of view, which is considered to be 115.6 degrees in Figure 7).

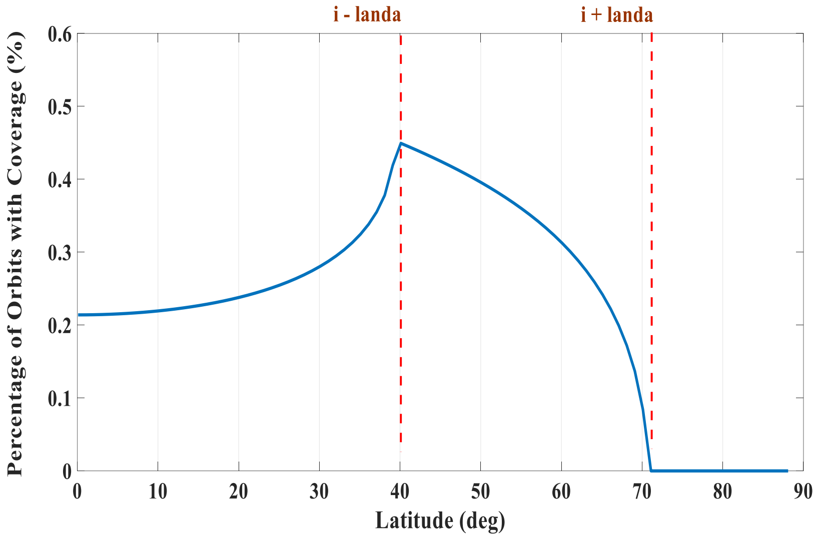


Figure 6. Alternative representation of a rotating ground track.

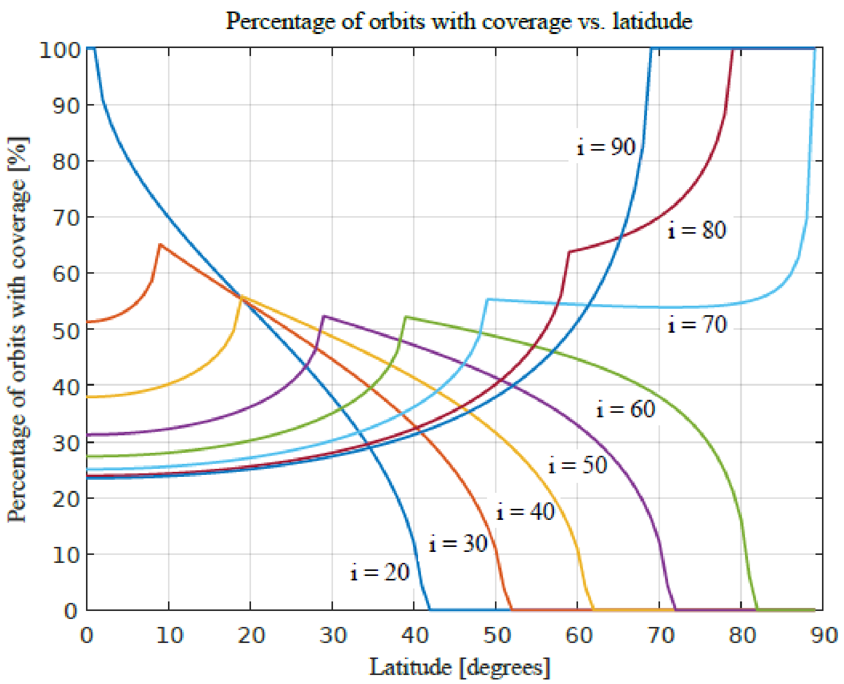


Figure 7. Coverage results for a satellite at 700 kilometers altitude and a minimum elevation angle of 20 degrees (corresponding to FOV of 115.6 degrees) at different geographic latitudes.

The optimal orbital inclination for maximum coverage in Iran's target region, which lies within the geographic latitude band of 25 to 40 degrees, is determined based on the above analytical algorithm by calculating the area under the coverage curve across different orbital inclinations and finding the optimal inclination such that the corresponding area is maximized. The results of this analysis are shown in Figure 8.

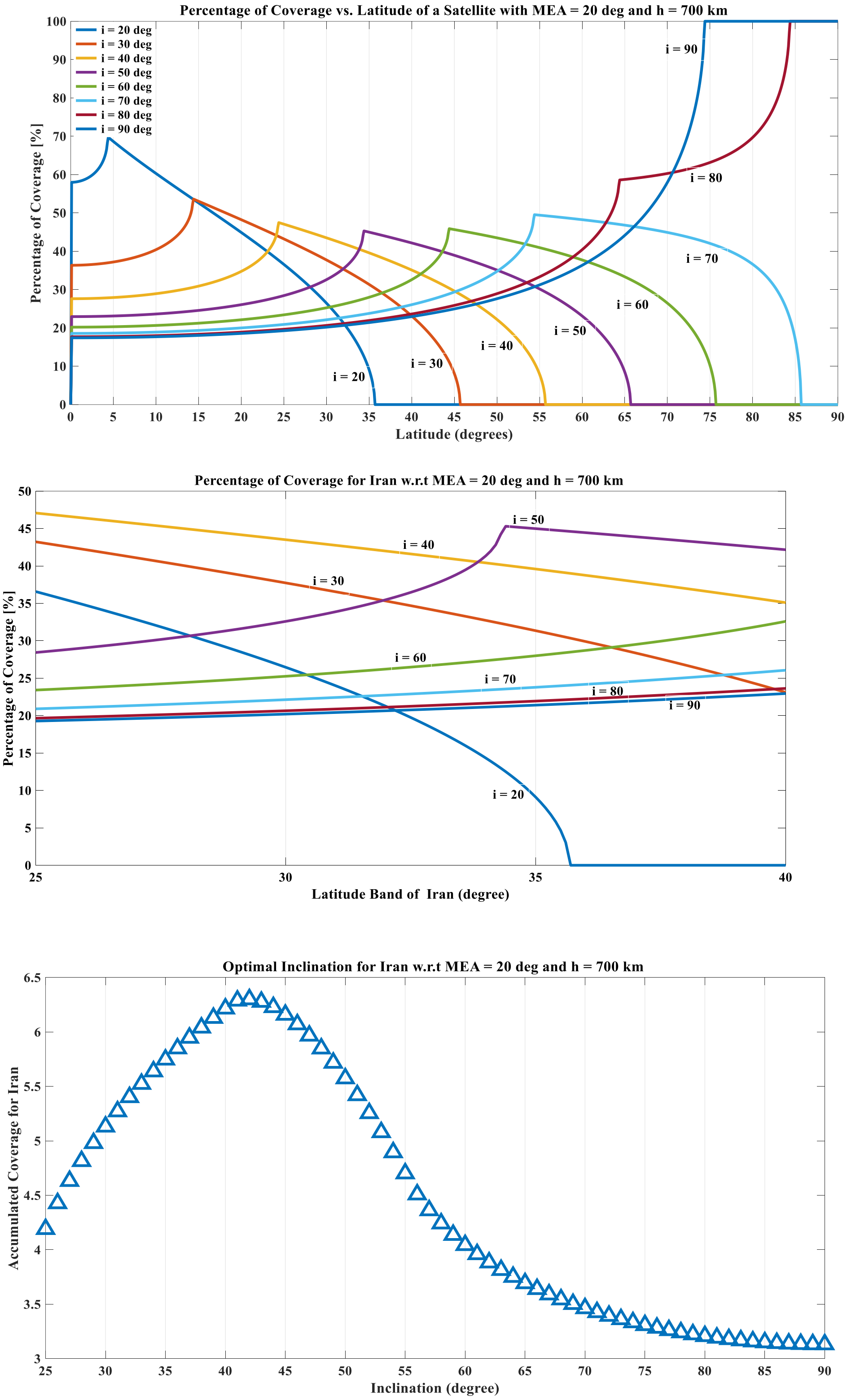
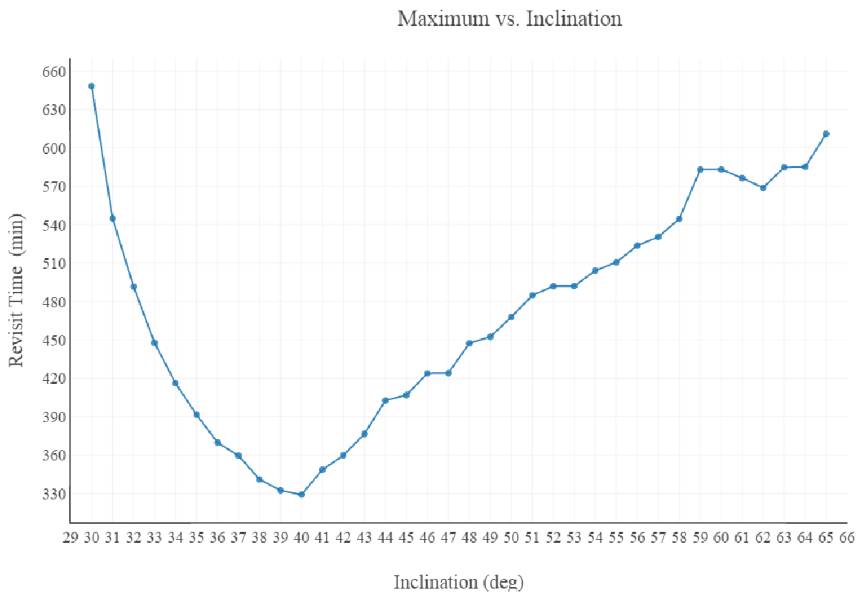


Figure 8. Coverage graphs based on geographic latitude and orbital inclination for a LEO satellite at 700 kilometers altitude and a minimum elevation angle of 20 degrees (corresponding to FOV of 115.6 degrees).

4 VALIDATION OF RESULTS USING STK SOFTWARE

This section presents the simulation results of the maximum revisit time for Iran's target region at different orbital inclinations, considering a satellite in a circular orbit at 700 kilometers altitude with a minimum elevation angle of 20 degrees using STK software. Figure 9 displays the results of this analysis. The optimal orbital inclination for achieving maximum coverage in Iran's target region corresponds to the inclination where the maximum revisit time for this region is minimized. Based on Figure 9, the optimal orbital inclination is 40 degrees,, which aligns with the results obtained from the proposed analytical methods. As demonstrated in the simulations of the proposed analytical algorithms, the optimal inclination of a nominal satellite in a circular orbit at 700 kilometers altitude with a minimum elevation angle of 20 degrees for providing maximum coverage in Iran's target region is determined to be 39 degrees based on the first analytical algorithm (two-dimensional mapping method), which has a 5.2% error compared to the actual value of 40 degrees based on the simulation by STK software. The optimal orbital inclination, considering identical conditions based on the second analytical algorithm (coverage as a function of geographic latitude method), is determined to be 42 degrees, which has a 5% error compared to the actual value. As observed, the first analytical method is more accurate than the second method. The higher accuracy of the first analytical method in calculating the optimal orbital inclination based on the maximum regional coverage criterion is because this method focuses on ground targets solely within Iran's region, whereas the second method considers all ground targets within Iran's geographic latitude band (25 to 40 degrees). The results indicate that both analytical methods possess high accuracy and can be used in the preliminary mission design phase for quick and simple comparisons between different conditions.

For additional validation, we reproduced the results of the study by Shin et al. [27], [28]. In this reproduction, we adhered to the parameters outlined in their paper, including a satellite orbit altitude of 550 km, a fixed payload field of view (FOV) of 60°, and a half-angle of the instant coverage range (α\alphaα) of 30°. For the specific case of Seoul, the algorithm determined an optimal inclination of 39.0° to maximize the geometrical coverage of the region. Following this methodology, we validated the results for the 10 regions of interest near the Korean Peninsula (Fig. 7 of their paper), each defined with a radius of 50 km. This successful validation reinforces the reliability of their analytical approach and establishes the robustness and applicability of our proposed methods for calculating optimal inclination.



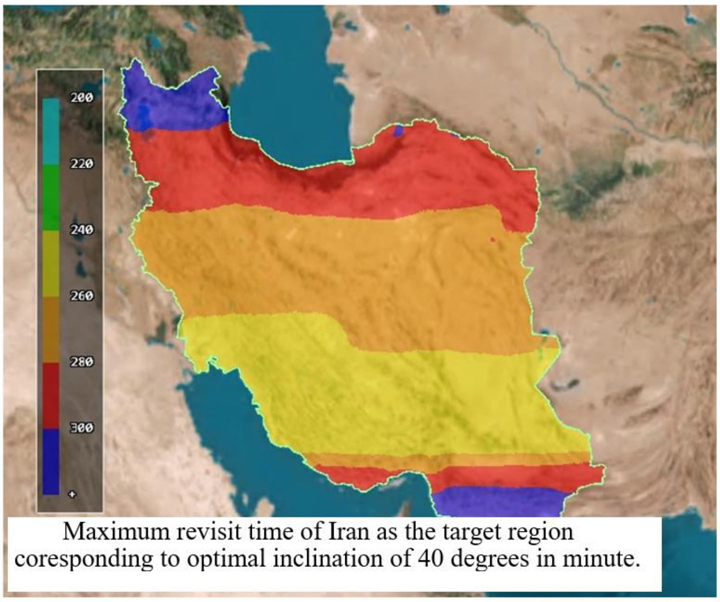


Figure 9: Maximum revisit time of Iran as the target region corresponding to the optimal inclination of 40 degrees per minute.Simulation Results of Maximum Revisit Time for Iran's Target Region by a Satellite in a Circular Orbit at 700 Kilometers Altitude and a Minimum Elevation Angle of 20 Degrees.

5 CONCLUSION

In this study, two analytical algorithms were developed to determine the optimal orbital inclination for micro-satellites in low Earth circular orbits based on the maximum regional coverage criterion. The first algorithm employs a two-dimensional mapping method, leveraging the satellite's coverage range and the geographic positions of ground targets to calculate the optimal inclination. For example, for a satellite at 700 kilometers altitude with a minimum elevation angle of 20 degrees (corresponding to a FOV of 115.6 degrees), the optimal inclination was determined to be 46 degrees for Tehran and 40 degrees for Iran's target region.

The second algorithm, which calculates coverage as a function of geographic latitude, determined an optimal inclination of 42 degrees within Iran's geographic latitude band (25 to 40 degrees) under similar conditions. Validation through simulations using STK software showed errors of 2.5% and 5%

for the first and second algorithms, respectively, demonstrating their accuracy and suitability for preliminary mission design.

To strengthen the validation process, the study extended beyond STK simulations by comparing the results with the findings of Shin et al. (2021), who conducted a similar analysis for regional coverage optimization. Using their parameters, including a satellite orbit altitude of 550 kilometers and a FOV of 60°, we validated the consistency of the proposed algorithms, confirming an optimal inclination of 39 degrees for Seoul. This additional validation reinforces the reliability of the methods. However, attempts to validate the algorithms using data from previously executed satellite missions were limited by the lack of publicly accessible data, as such information is often restricted for proprietary or security reasons. This limitation is acknowledged, and future research is proposed to explore real-world validation opportunities further.

The proposed algorithms also hold significant potential for practical applications, including disaster monitoring and communication satellite design. By determining the optimal orbital inclination for efficient regional coverage, these methods can be directly applied to scenarios requiring targeted geographic coverage. For example, they can enhance regional disaster monitoring by ensuring timely revisit times for affected areas or improve the design of communication satellites for densely populated regions, providing reliable and efficient coverage. The algorithms' computational efficiency and flexibility make them highly relevant for addressing practical challenges in satellite mission design.

In summary, the presented analytical algorithms provide a novel and computationally efficient framework for determining the optimal orbital inclination for regional coverage. They eliminate the need for resource-intensive simulations and optimization processes, offering a valuable tool for preliminary mission design.

The inclusion of validation steps and discussions of practical applications further underscores the contribution of this work to satellite mission planning. Future efforts should focus on integrating real-world data and applying these algorithms in operational missions to enhance their robustness and real-world impact.

CONFLICT OF INTEREST

No potential conflict of interest was reported by the authors.

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