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LEO Communication Constellation Design Using Street of Coverage (SOC) Technique

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Abstract. The African Space Agency aims to unify the available resources across the African Continent. One of these resources includes communication services and internet connectivity to cover African areas. To achieve this goal, this study proposes a standalone system, namely a satellite constellation system applying the Street of Coverage (SOC) method. This method includes three configurations, inclined orbit, symmetrical polar orbit, and non-symmetrical polar orbit. A Low Earth Orbit (LEO) is considered due to its advantage in its low latency, making it ideal for communication purposes. A mathematical model governing the SOC constellation is deduced. Results are visualized and analyzed using the System Tool Kit (STK) application. A validation case is proposed by comparing consistency with a well-known satellite constellation OneWeb produced by the international company Eutelsat-group. Two potential satellite constellations are proposed to provide coverage across underserved African areas. In the first configuration, the symmetric polar constellation is utilized with 612 satellites uniformly distributed along 18 planes. This system is characterized by its low cost, high efficiency, and optimum performance as a standalone solution. In the second configuration, the equatorial satellite constellation with 25 satellites uniformly distributed along the equatorial plane is analyzed. This configuration is a more economical solution that uses fewer satellites and relies on back-hauling between available communication networks.

Keywords—African Space Agency, Street of Coverage, Constellation, Inclined Orbit, Symmetrical Polar Orbit, Non-symmetrical Polar Orbit.

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1. Introduction

The selection of the Low Earth Orbit (LEO) communication constellation initiates from the concept of utilizing multiple smaller and cost-effective satellites instead of using a single, standalone, large, and expensive satellite in Geostationary Earth Orbit (GEO) [1]. This option decreases the system resilience, as the failure of one small satellite has a minimal impact on the overall performance, unlike using a one standalone expensive GEO satellite. The Street of Coverage (SOC) is one of the most commonly used techniques in providing continuous coverage over areas of interest, whether globally or within a definite area specified by latitude and longitude bounds [2], [3]. In 1961 – R. D. Luders: Developed the theory of "street-of-coverage" constellations satellites in equally spaced polar orbits and derived formulas relating satellite count, orbit inclination, and coverage latitude [15], in 1974 – R. D. Luders & L. J. Ginsberg: Generalized earlier coverage analysis to continuous zonal coverage at any inclination, treating inclination and coverage latitude as continuous variables [12], in 1978 – D. C. Beste: Developed an analytical design method for optimal continuous coverage constellations, particularly non-symmetric polar constellations. Beste's method systematically minimized satellite count for single, double, and triple coverage at given elevation angles [19]. J. Adams & D. Rider in 1987 Used a computational search to design optimally phased polar constellations with the minimum satellites for continuous single or multi-fold coverage above a given latitude [16], in 1998 – Thomas J. Lang William S. Adams: compared various satellite constellation designs for continuous global coverage, evaluating trade-offs such as satellite count, coverage uniformity, and revisit times [17], Quan Chen, Yuzhu Bai, Lihu Chen and Ziyan Pang in 2017: present a design framework for LEO constellations to provide internet services using the Streets-of-Coverage (SOC) method, approach to optimizes constellation parameters to achieve continuous coverage while minimizing satellite count [9].

In the context of the African continent, the population is about one and a half billion people [4]. According to the International Telecommunication Union (ITU), only 37% of the African population benefits from internet services [5] such as OneWeb, Starlink, and Iridium, which consist of 648, 12000, and 66 satellites, respectively. These constellations depend on both the Walker and the SOC satellite constellation techniques [6]– [8]. In this study, the desired African communication constellation satellite will be designed to address the internet coverage needs of the remaining 63% of the population. According to the population density and areas with no internet services, the constellation will be analyzed. A key factor impacting the total number of satellites required is the capacity of the satellite. For guidance, the OneWeb satellite constellation will be implemented, which includes a data rate of 7.2 Gbps and contributes to a cumulative usable capacity of 2.65Gbps [9].

The paper is organized as follows: the coverage geometry of a single satellite is introduced in Section 2. The SOC is detailed in Section 3. Section 4. presents the implementation of the SOC strategy and gives a first proposal for the satellite constellation to cover the African continent. Then, a validation case of the SOC strategy is proposed in Section 5. Finally, the conclusions of the proposed study are summarized.

2. Coverage Geometry of a Single Satellite

The coverage geometry of a single satellite, as illustrated in Fig.1, is defined as the spherical surface created by the earth's surface meeting the satellite-centered cone [3,10]. A spherical portion of the earth's surface can be covered by a satellite with height h, half-beam angle α, and minimum elevation angle σ. In this study, the coverage angle θ, which is the most important factor in determining the pattern of the constellation, equation 1 is defined as the geocentric half- cone angle of the coverage zone and it is related to the half-beam angle [9,10],

$$\theta = \arcsin\left(\frac{h + R_e}{R_e}\ \sin\alpha\right) - \alpha \tag{1}$$

The relation between half beam angle (α) and minimum elevation angle (σ) stated in equation (2)

$$\sigma = \arccos\left(\frac{h+R_e}{R_e}\ \sin\alpha\right) \tag{2}$$

For a fixed satellite altitude h = 800 km, both the coverage angle and the minimum elevation angle are determined versus the half-beam angle, as shown in Fig. 2. It can be concluded that the single coverage angle θ increases as the half-beam angle increases, at h = 1200 km and = 32.7 deg, θ = 7.23 deg and σ = 50 deg.

3. Methodology

By applying the **SOC concept**, multiple satellites are placed in circular orbits within a single plane at the same altitude. This configuration ensures continuous visibility of the SOC [11] as shown in Fig.3. An analytical process is implemented to find the number of satellites needed to cover the area of interest, utilizing the

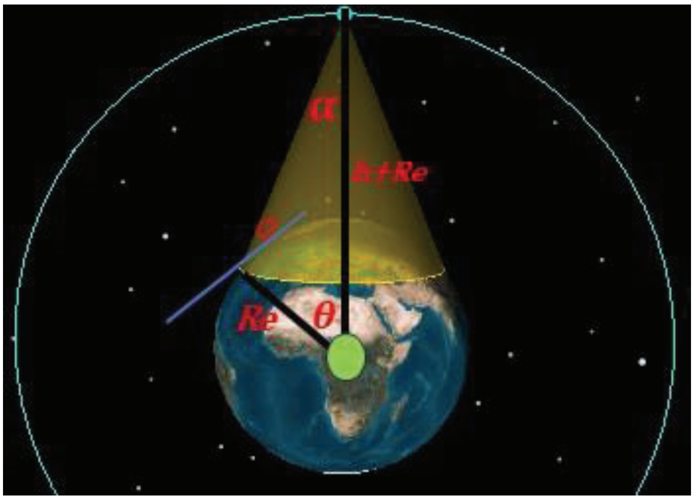

Figure 1. Coverage Geometry of single satellite.

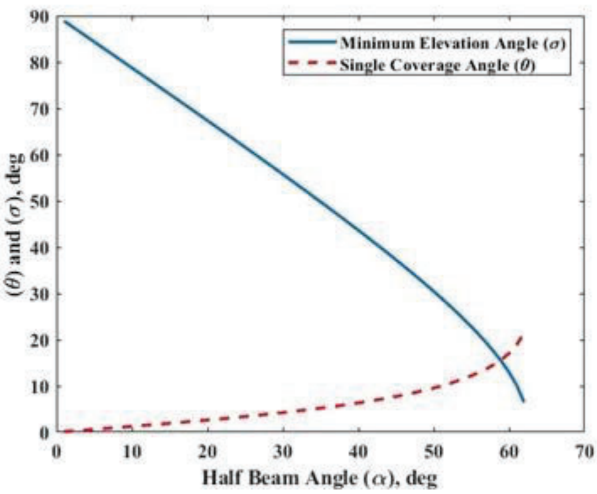

Figure 2. The satellite coverage versus its half-beam angle, h = 800 km.

continuously viewable overlapped coverage zones of nearby intra-plane satellites. Constellation configuration using the SOC approach displays the following characteristics [3], [10]:

- Every orbit, circular in shape, has the same height *h,* and inclination *i*.

- The constellation is made up of n_1 orbit planes with n_2 satellites in each.
- The distribution of satellites in every plane is uniform.

The street width ψ can be calculated using spherical trigonometry [9] as,

$$\cos\theta = \cos\psi\ (\pi/n_2) \tag{3}$$

The SOC technique takes into account streets that are continually covered disregarding coverage beyond these regions. As a result, it is possible to eliminate the phase difference between neighboring plane satellites, and the circular coverage zones are reduced to strips that represent each plane. The next step in the constellation design process includes determining the width of each constellation configuration to cover the designated area of interest [11] [12].

3.1. Inclined orbits

Applying the SOC strategy to create a satellite constellation for inclined orbits [3], the zonal area, which extends across the equator from the maximum latitude (ϕ_{max}) to the minimum latitude (ϕ_{min}) is constantly covered. All orbital planes are inclined with angle i, and the n_1 orbital planes are dispersed uniformly over the equator, as shown in Fig. 4.

These inclined orbital planes n_1 are projected on the earth's surface, where the earth will be divided into two equal parts above and under the equator (latitude bounds) producing a pattern of meshes equal to (n_1 −1). The intersection latitude measured from north to south is determined by,

$$\phi_j = arctan[tan\ i\ .\cos(j\pi/n_1)] \tag{4}$$

where, $j = 1,...,n_1-1$, and $-i < \phi_j < +i$ as $\phi_0 = i$ and $\phi_n = -i$. Note that the northernmost grid node's latitude is ϕ_1. If $\phi_{max} \le \phi_1$, then only the coverage within the inner mesh sections is to be considered. Otherwise, as shown in Fig. 6, additional coverage outside of the n_1-1 layer meshes, denoted as ψ_{ext} should also be considered. In this configuration, the point P represents the center of the inscribed circle that tangents to all four edges of the given mesh. The angle X_U defines the orientation between P and the top vertex, while ψ_{min} represents the angle between P and any of the mesh borders, as well as the minimum street width required to ensure full coverage of the m^{th} layer mesh.

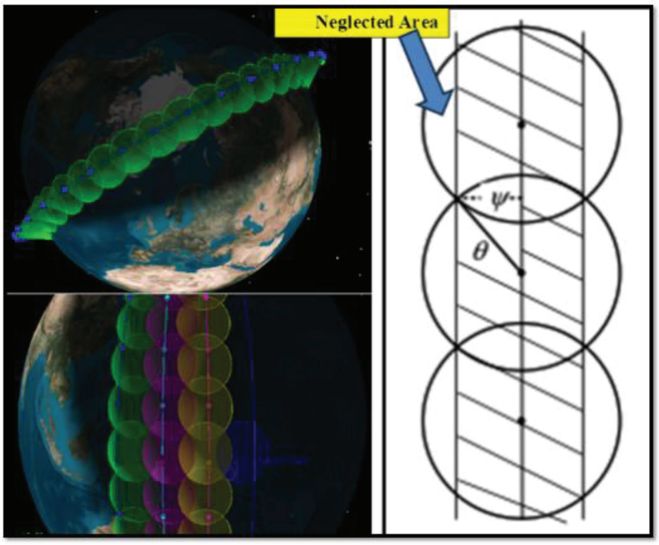

Figure 3. Street of Coverage.

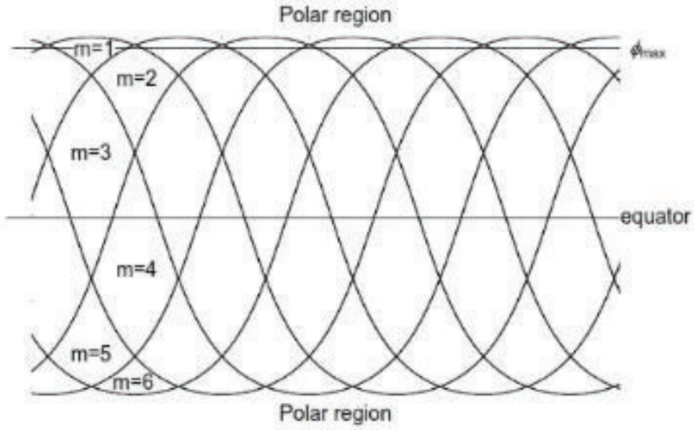

Figure 4. Geometry of the mesh

The value of ψ_{min} can be determined as

$$\sin\psi_{min,m} = \sin X_U \cos i/\cos\phi_{m-1} \tag{5}$$

$$X_U = arctan\Big\{\sin\Big(\frac{m\pi}{n_1}\Big)\sin\Big(\frac{\pi}{n_1}\Big) tani\Big\{1+\cos\Big(\frac{m\pi}{n_1}\Big)\cos\Big(\frac{\pi}{n_1}\Big)\cos\Big[(m-1)\frac{\pi}{n_1}\Big]tan^2 i\Big\}^{-1}\Big\} \tag{6}$$

To compute the number of satellites required to cover a certain region, Fig.5 illustrates the general geometry of the m^th^-layer mesh. Otherwise as Fig. 6 shows, extra coverage outside of the n_1–1 layer meshes ψ_{ext} should also be taken into account.

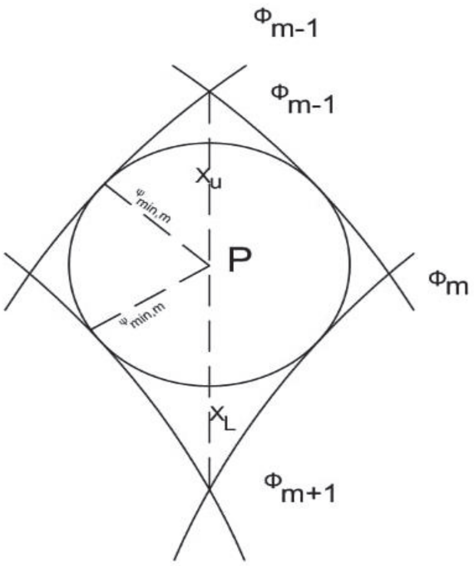

Figure 5. The geometry of the mth-layer mesh.

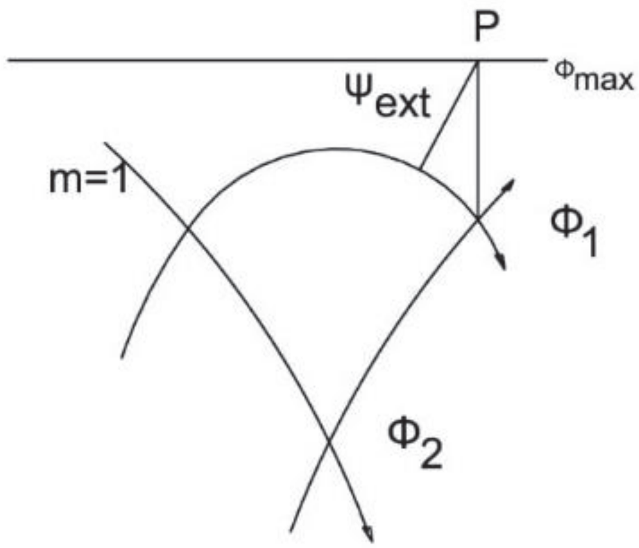

Figure 6. Extra coverage ψ_{ext} outside of the n_1-1.

The maximum value of $\psi_{min,m}$ for the meshes that must be covered is the total necessary width of streets ψ_{min}. For the condition of $\phi_{max} \geq \phi_1$, the required street width to cover the external region ψ_{ext} calculated as,

$$\psi_{ext} = arcsin[\sin\phi_{max} \cos i - a \cos\phi_{max} \sin i \cos(\pi/n_1)] \quad (7)$$

Under these circumstances, the necessary minimum width is computed as,

$$\psi_{min} = max\{\psi_{min,1}, \psi_{min,2}, ..., \psi_{min,n_1-1}, \psi_{ext}\} \quad (8)$$

Corresponding to Fig. 3, which illustrates the relation between the single coverage angle θ and width of the street ψ, if $\theta \leq \psi_{min}$ means that it is not feasible to build streets with the necessary width i.e the coverage angle of a single satellite is not larger than the required minimum street width, when $\theta > \psi_{min}$ means that the performance of single coverage is good and can calculate the number of satellite per plane (n_2) to cover the required region by equation 9. Then, the required total number of satellites N is given by,

$$n_2 \geq \frac{\pi}{arccos(\cos\theta / \cos\psi_{min})} \quad (9)$$

$$N = n_1 \left[\frac{\pi}{arccos(\cos\theta / \cos\psi_{min})} \right], \theta > \psi_{min} \quad (10)$$

3.2. Symmetrical polar constellation

Polar satellites have an inclination i of 90°, and to fully exploit the coverage of ascending and descending orbits, the ascending nodes typically spread throughout $0,\pi$. The n_1 planes in a symmetrical polar constellation are consistently separated by Δ, where $\Delta = \pi/n$. Latitudes from lower latitude parts until the equator are more difficult to cover as it is the largest distance on the earth surface. Polar regions are the most likely to be covered since all of the polar constellations orbits cross at two poles. The equator can only be continually covered after continuous global coverage has been attained. Thus, the minimum street width needed to spread split along the equator should follow,

$$\psi_{min} = \frac{\pi}{2n_1} \quad (11)$$

Then, the required number of satellites N needed in a symmetrical polar constellation to cover the whole Earth is iteratively obtained by satisfying equation (12) as,

$$N = n_1 \left[\frac{\pi}{arccos(\cos\theta / \cos(\pi/2n_1)} \right], \theta > \frac{\pi}{2n_1} \tag{12}$$

3.3. Non-Symmetrical polar constellation

The extra coverage between any two consecutive orbital planes is effectively wasted as mentioned in Fig. 3, as coverage extending beyond the designated street width is not utilized.

There are two types of interfaces between any two adjacent orbits in polar constellations, co-rotating and counter-rotating interfaces, as illustrated in Fig. 7, with a corresponding polar view shown in Fig. 8. The angular separations these interfaces are stated as,

$$\Delta_1 = \theta + \psi \tag{13}$$

$$\Delta_2 = 2\psi \tag{14}$$

The co-rotating interface allows the ideal phase shift to provide the greatest continuously covered regions while maintaining the fixed relative positions of neighboring satellites and allowing for the arrangement of phase separation between satellites in adjacent orbits. Nonetheless, as counter-rotating interfaces experience rapid variations in relative positions, neighboring orbits ought to be close enough to one another to create continuous SOC.

In a polar constellation with n_1 orbital planes, there are two counter-rotating interfaces and $2(n_1 - 1)$co-rotating interfaces. Their relationship is expressed as,

$$(n_1 - 1)\Delta_1 + \Delta_2 = \pi \tag{15}$$

The minimum required street width can be determined using Equation 16, which is then used to calculate the total number of satellites needed for full coverage, as given by Equation 10.

$$\psi_{min} = \frac{\pi - (n_1 - 1)\theta}{n_1 + 1}, n_1 > \frac{\pi}{2\theta} \tag{16}$$

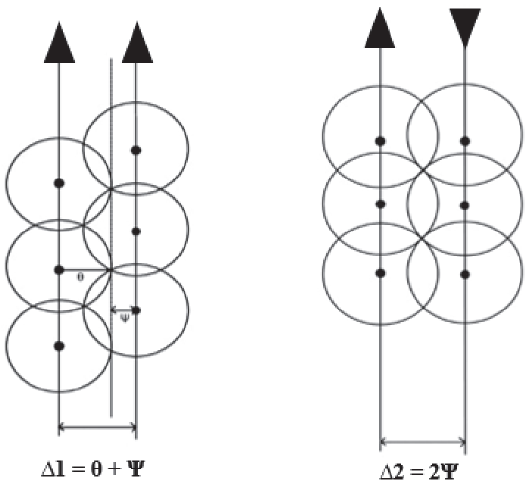

Figure 7. Co-rotating and counter-rotating interfaces.

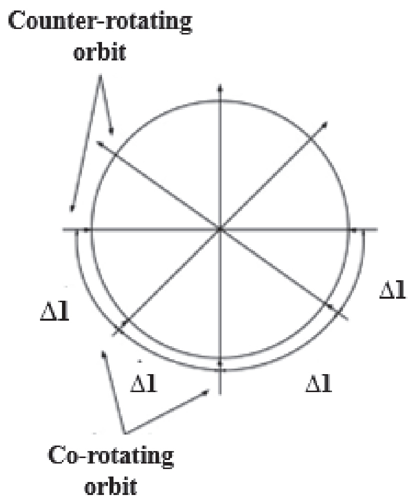

Figure 8. Polar view.

To summarise the previous equations for mentioned three different SOC configuration, Fig. 9. flow chart of a pseudo-code, which illustrate the steps to achive the total number of satellite prodcing full coverage.

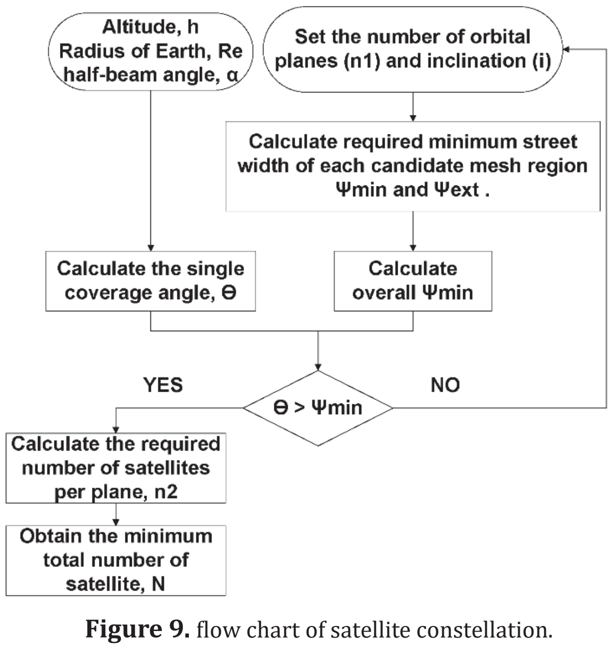

Figure 9. flow chart of satellite constellation.

4. Results and Discussion

Following the description of the above three SOC techniques, each of them is implemented separately on the MATLAB application[13]using the inputs and assumptions listed in Table 1. Additionally, each configuration is implemented in the STK application [14] to visualize and analyze its outputs. This proofs that the results provide full coverage of the area of interest and help determine the number of satellites in use at any given time simultaneously.

The study results allow for the use of a large number of satellites, which are small in size and have a long operational life time. These satellites are replaced upon reaching the end of their expected life time. The effects of drag were not specifically analyzed, as the satellites operate at an altitude of 1200 km, where its influence is minimal and can be mitigated through satellite control [18]. Additionally, collision avoidance is managed (changing satellite position) through satellite control systems.

Table 1. Data inputs and assumptions

Data inputs	Assumption
Half Beam Angle, α = 32.7	Earth is spherical.
Satellites Altitude, h = 1200 km	Coverage regions are simplified as strips (Street).
Latitude bounds, ϕ = 40	Orbit planes are equally distributed along the equatorial plane in the case of an inclined constellation.
Satellite data rate = 12 Mbps	African populations are uniformly distributed within Africa.
Satellite capacity = 2.65 Gbps	Every person will consume 1mbps.

4.1. Inclined orbit constellation

The total number of satellites N at different inclinations (i = 35,40, and 45°) and its relation to the number of planes n_1 are shown in Fig. 10 which shows that the better total number of satellites N produced at the smallest inclination. Applying the results produced from the MATLAB application related to the constellation pattern which consists of N = 703 and n_1 = 19 in the STK application, using coverage definition and figure of merit tools to ensure full coverage of the demand latitude pattern, by selecting area of interest latitude bands contain African continent, creating constellation by assets (satellites sensor with previous specsficaion), propagate scenario and produce report ensuring full continuous coverage at every secound. Fig.11 shows the constellation pattern that proves full coverage. The mentioned configuration of the constellation yields an average of seven simultaneous satellite connections for any user within the African continent, assuming every person will consume 1mbps and according to table 1 the satellite capacity = 2.65 Gbps, then one satellite cover 2650 users, using Fair Consumption Method, leads to one satellite covered 26500 user at the same time . This can support the internet service to approximately 19 million users simultaneously.

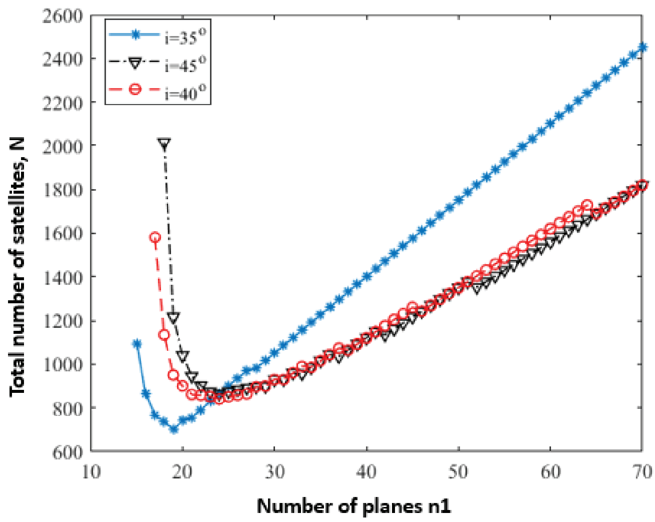

Figure 10. Total number of satellite required to cover a zonal region 35° from the equator.

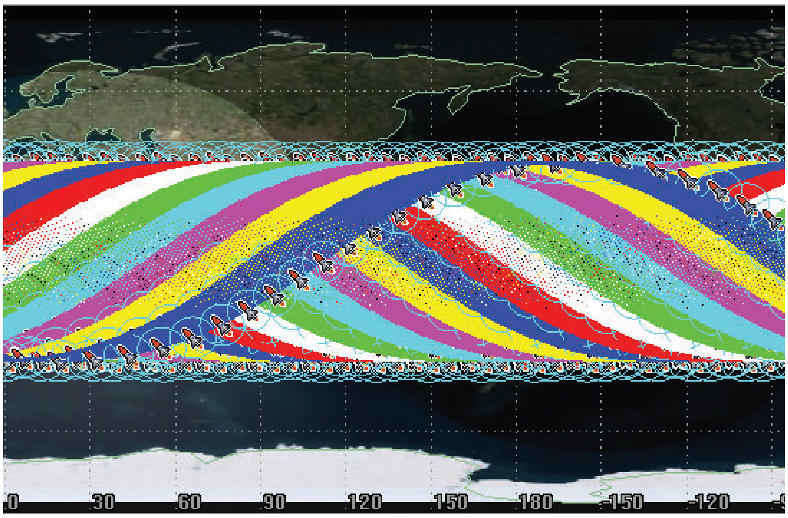

Figure 11. 2D inclined constellation pattern.

By applying this configuration at inclination = zero (equatorial plane) the total number of satellites that produced continuous connection with the African continent equals 25 satellites, this constellation can be used for communication back-hauling between local ground networks and providing internet service outside the urban areas where a low elevation angles between users and satellite are not obscured. Fig. 12 shows the visualization of the equatorial constellation.

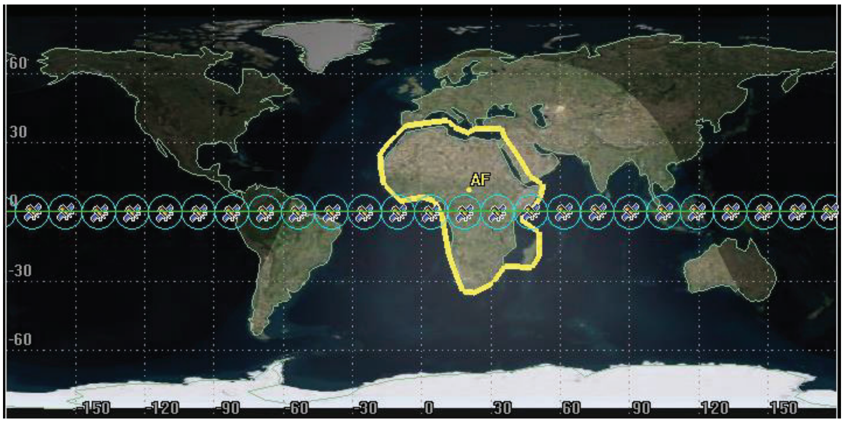

Figure 12. The equatorial constellation.

4.2. *Symmetric polar constellation*

To cover the same zonal region, which is the African continent. The influence of the number of planes (n_1) over the total number of satellites N is obtained when the design provides full coverage of the Earth. The symmetric polar (inclination = 90) constellation method yields a constellation configuration, which consists of N = 612, and n_1 = 18, applied in the STK. Fig.13 shows coverage of a symmetrical constellation pattern that provides full coverage to the entire Earth, where each user is connected by an average of two satellites. This can support the internet service to approximately 17 million users simultaneously.

4.3. *Non-symmetric polar constellation*

This constellation pattern consists of N = 486, and n_1 = 18, resulting in an average of one satellite per user. . This can support the internet service to approximately 13 million users simultaneously. A comparison between Symmetrical and Non-symmetrical polar (inclination = 90) constellations from the point of view of the total number of satellites is shown in Fig. 14, which illustrate achieving the minimum total number of satellite produced full coverage in case of symmetrical polar is better than in case nonsymmetrical polar constellation.

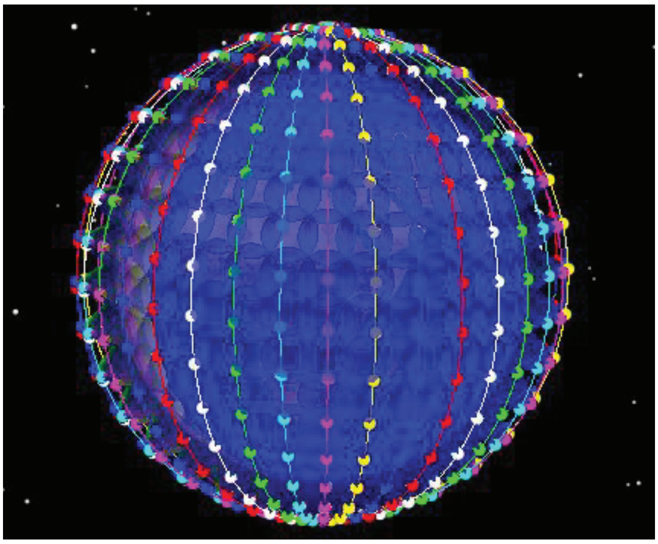

Figure 13. Symmetrical constellation pattern.

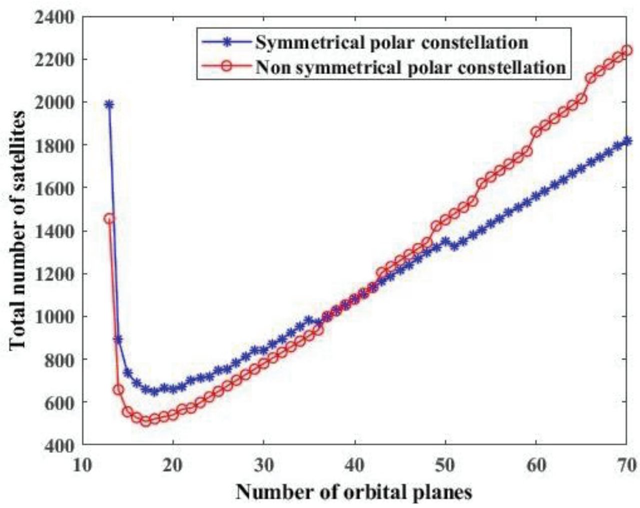

Figure 14. The total number of satellites as a function of number of orbital planes.

Finally, it turns out that the number of satellites produced in the inclined case is significantly higher than the number of satellites produced in the symmetric and non-symmetric polar cases. This difference in the number of satellites due to the highest of overlap between projection of satellites' payloads on the Earth surface as shown in Fig. 15.

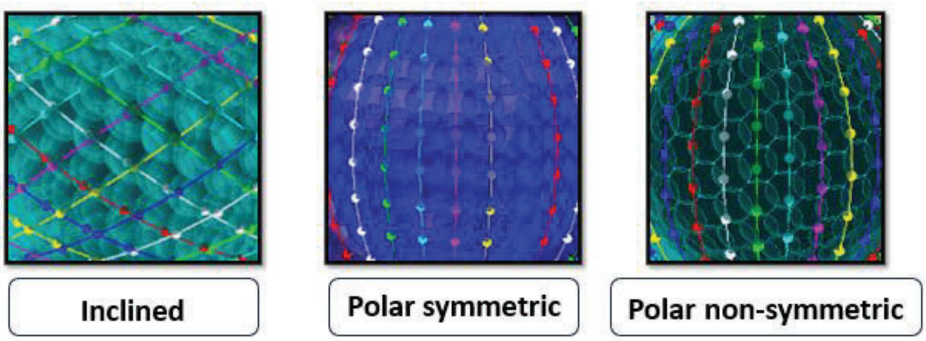

Figure 15. Satellites overlap in different orbit constellation configurations.

5. Conclusion

This study analyzed different constellation configurations to determine the most efficient satellite placement for continuous coverage over the African continent. These configurations include inclined, symmetric polar, and non-symmetric polar constellations. The payload half-beam angle plays a crucial role in defining the optimal constellation pattern. The inclined configuration offers advantages for high-density regions, making it best suited for regions with high population density or greater data transfer capacity requirements. But, it is the least efficient in terms of total satellite count with 703 satellites. The non-symmetrical method, including 486 satellites, emerges as the most efficient and practical choice for full African coverage, and near-global reach with fewer satellites, making it the more practical choice for lower-population regions. The symmetrical configuration with 612 satellites, makes it less favorable. For economical solution that uses fewer satellites and relies on back-hauling between available communication networks, the equatorial satellite constellation with 25 satellites uniformly distributed along the equatorial plane is choice.Finally, the inclined SOC configuration may require further refinement to optimize the satellite count and make it more practical.

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