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Research Article

Low-Orbit Large-Scale Communication Satellite Constellation Configuration Performance Assessment

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A constellation configuration performance evaluation method is proposed for the performance evaluation of the low-orbit large-scale communication satellite constellations. The practicality and feasibility analysis of the constellation configuration is mainly studied from the constellation coverage performance. Based on the consideration of the coverage performance of the LEO satellite constellation, four simulation models are established for the single coverage rate, observation elevation angle, number of visible satellites under different observation elevation angles, and coverage efficiency of the constellation. A population distribution density function is established according to the characteristics of population distribution to find the average minimum observation elevation angle and the average number of visible satellites under the population distribution. The evaluation method is applied to three typical low-orbit large-scale communication satellite constellations, Telesat, OneWeb, and Starlink, to derive the coverage performance index values of each constellation and to compare and analyze the characteristics of the three constellations. The results show that the evaluation method can evaluate the configuration performance of different types of LEO large-scale constellations and provide a basis and reference for the optimal design and evaluation of future LEO large-scale constellation configurations.

1. Introduction

Constellation performance assessment is an effective way to judge whether a constellation can meet design standards. With the rapid development of nanosatellite technology, low-orbit satellite constellations are becoming a key research priority for major spacefaring nations, and the performance assessment of low-orbit satellite constellations has become more important. Unlike medium- and high-orbiting constellations, LEO satellite constellations have a larger number of satellites, a more complex structure, and a relatively longer deployment cycle, so the assessment methods and criteria are different. The study of the performance assessment of LEO constellations is important for improving the construction of LEO constellations and for optimizing the design of LEO constellations. When analyzing the constellation configuration, two main types of indicators are analyzed: coverage performance and cost of the constellation. Yu et al. provided an overview of the design optimization of communication satellite constellations and analyzed performance indicators such as coverage performance, intersatellite links, and system cost [1]. Chen et al. proposed a method to determine the minimum observation elevation angle and the average observation elevation angle of the constellation system for any type of ground target and analyzed the coverage performance of the constellation system [2]. Wang et al. studied the performance evaluation of small satellite reconnaissance constellations from three aspects: coverage, cost, and resilience, and established a capability evaluation model for each of these three aspects [3]. Liu et al. analyzed the coverage capability of the Starlink constellation, mainly analyzing the amount of variation in the number of visible satellites with latitude [4]. At present, there are few studies on the performance assessment of low-orbit large-scale communication satellite constellations, and the assessment methods for constellation configurations are not uniform. A reasonable and effective assessment method is needed to analyze low-orbit large-scale communication satellite constellation configurations. Aiming at the characteristics of low-orbit large-scale communication satellite constellations and combining the evaluation models of medium- and high-orbit satellites or constellations, this paper improves the current evaluation method, establishes an evaluation model applicable to the configuration of low-orbit satellite constellations, and uses the simulation model to compare and analyze the current typical low-orbit constellations [5, 6].

2. Coverage Performance Analysis

In the performance analysis of a constellation configuration, the coverage performance of the constellation is the most important indicator for judging the constellation design. There are many coverage performance indicators, and it is necessary to establish coverage performance indicators, which are shown in Figure 1, based on the need for a constellation of low-orbiting large-scale communication satellites to meet the characteristics of uninterrupted global coverage [7–14].

Low-orbit constellations are generally less than 1,500 km high, and the coverage area of a single satellite is much smaller than that of medium- and high-orbit satellites. Three or four satellites in high orbit can achieve ground coverage and a dozen or so in medium orbit, while hundreds or thousands of satellites in low orbit are required. A low-orbiting satellite has a spherical crown shape on the surface and covers a small area, requiring a reasonable constellation configuration to achieve global coverage.

In the analysis of the coverage performance of a constellation, the grid point method is now the more common method. As shown in Figure 2, let the grid area covered by a single satellite in the constellation bes; then, the grid area S_{cov} covered by a constellation containing n satellites can be expressed as

$$S_{\text{cov}} = \{s_1 \cup s_2 \cup s_n\} \tag{1}$$

Let the Earth's surface grid area be Ω. Single coverage rate P_{cov} is defined as the ratio of the constellation's coverage of the Earth's grid area S_{cov} to the Earth's surface grid area Ω , and when the ratio of the constellation coverage is 1, the constellation has global coverage of the Earth. The single coverage ratio can be expressed as

$$P_{\text{cov}} = \frac{S_{\text{cov}}}{\Omega}. \tag{2}$$

When the satellite achieves T coverage of a point on Earth, the T point will form a certain angle with the satellite, the observation elevation angle decreases, the link attenuation between the star and the ground will increase, and there will also be satellite antenna quality factor (G/T) to reduce the impact of problems, making the coverage performance of communication satellites reduced; when the minimum observation elevation angle is less than 10°, it is difficult to meet the communication needs of general ground user access. Therefore, when designing the configuration of the LEO satellite constellation, the observation elevation angle is made as large as possible to ensure high communication quality. At a given moment, let the coordinates of a point on the Earth's surface in the geocentric inertial coordinate system be $T(x_1, y_1, z_1)$, let the coordinates of a satellite in the constellation be $S(x_2, y_2, z_2)$, and let the origin be O. The expression for the observed elevation angle σ of the satellite at this point can be obtained by vectorial means:

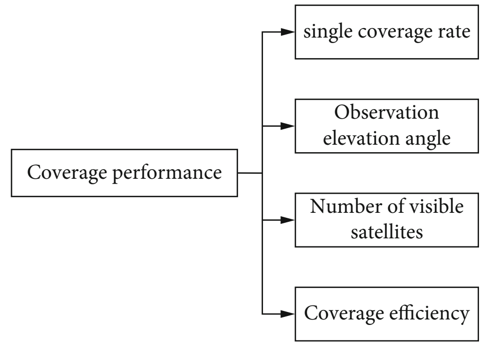

Figure 1: Coverage performance indicators.

$$\begin{cases} \mathbf{TS} = (x_1 - x_2, y_1 - y_2, z_1 - z_2) = (x_3, y_3, z_3), \\ \sigma = \arcsin\left(\dfrac{(x_3, y_3, z_3)\cdot(x_1, y_1, z_1)}{\sqrt{x_3^2 + y_3^2 + z_3^2}\cdot\sqrt{x_1^2 + y_1^2 + z_1^2}}\right), \end{cases} \tag{3}$$

where $\mathbf{TS} = (x_3, y_3, z_3)$ is the directional vector from the target point to the satellite. During the operation of the satellite, the latitude and longitude of its subsatellite point change all the time, which makes the observation elevation angle also change all the time, when the observation elevation angle reaches the minimum value, that is, the minimum observation elevation angle σ_m, which indicates the minimum transmission loss of the constellation to the ground, etc.

The number of satellites visible to ground users at a given observation elevation angle is also an important indicator for evaluating the coverage performance of a constellation. The higher the number of visible satellites at the same observation elevation angle, the higher the coverage weight of the constellation, and the better the assurance that users can communicate with the satellites at all times, and the better the coverage performance of the constellation.

3. Performance Analysis considering Population Distribution

In general, the coverage performance analysis of constellations only considers the coverage of the sphere by the constellation and does not take into account the influence of the population distribution. The population distribution at different latitudes varies considerably and requires different coverage performances from the constellation, which makes the results of the coverage performance analysis of the constellation different. Compared to medium- and high-orbiting satellite constellations, the distribution of low-orbiting satellite constellations at different latitudes also varies more significantly and the coverage performance varies more, so the impact of population distribution at different latitudes needs to be considered when analyzing the coverage performance of constellations. The literature [10] considers the population distribution when analyzing constellation performance but simply assumes that the distribution of satellites is more consistent with the population in terms of dimensionality and does not establish a model relating population to constellation configuration performance. The population on the earth's surface is unevenly distributed, so the need for coverage performance varies, with the vast majority of the earth's population distributed between 20° and 40° latitude and very little in areas above 70° latitude, no more than 0.1% in other latitudes, as shown in Figure 3.

Considering that the population distribution is different at different latitudes and the low-orbit large-scale communication satellite constellation is intended for network and satellite communications, we prefer to allocate more resources to the densely populated areas [15–17]. Therefore, when analyzing the average of the performance indicators, the weight of the densely populated latitudes will be larger. And the distribution of population with latitude distribution can be used to obtain the population distribution density function, which can be used as indicator weights for different latitudes, reflecting the overall situation of the minimum observation elevation angle and the number of visible satellites of the constellation and the demand for them from the population distribution. Let the latitude population distribution density function be Q_φ, and the weighting method for different latitudes can be represented by the population weighting ratio in Figure 3 [18–20].

Low-orbiting constellations have different minimum observed elevation angles for different latitudes due to the constellation configuration. Using the weighting function Q_φ, the expression for the average minimum observed elevation angle σ_{cw} under the population distribution can be obtained as

$$\sigma_{cw} = \int_{\varphi_s}^{\varphi_n} \sigma_m(\varphi) \bullet Q_\varphi \mathrm{d}\varphi, \tag{4}$$

where $\sigma_m(\varphi)$ is the minimum observed elevation angle as a function of latitude. Similarly, at a given observation elevation angle, let $N(\varphi)$ be the number of visible satellites at different latitudes, and the expression for the average number of visible satellites on the Earth's surface can be obtained as

$$N_{cw} = \int_{\varphi_s}^{\varphi_n} N(\varphi) \bullet Q_\varphi \mathrm{d}\varphi. \tag{5}$$

When a constellation achieves continuous coverage of the Earth's surface, overlapping areas between satellites cannot be avoided, so it is important to make the satellite coverage of the Earth as uniform as possible, and the less the additional coverage overlapping areas, the less the constellation resources wasted. In the literature [20], a generic coverage performance evaluation index is proposed, in which the minimum number of satellites required is used as the standard number of satellites for a constellation with the same coverage area and minimum observation elevation angle, and the ratio of the standard number of satellites to the actual number of satellites is then used as the performance index of the constellation coverage. However, the parameter used is the minimum elevation angle of the constellation, and the minimum elevation angle of constellations with different orbital inclination varies with latitude; moreover, the current low-orbit large-scale communication satellite constellation generally adopts a combination of different orbital inclination configurations, and the minimum elevation angle is not necessarily near the equator, not to mention the regularity of the minimum elevation angle distribution. In this paper, the minimum observation elevation angle is the average minimum observation elevation angle A under the population distribution, which not only reflects the characteristics of the minimum elevation angle distribution with latitude but also takes into account the influence of population weighting, making the evaluation results more accurate and more applicable to various configurations of low-orbiting large-scale communication satellite constellations. The expression for the semigeocentric angle of the satellite's ground coverage circle can be obtained as

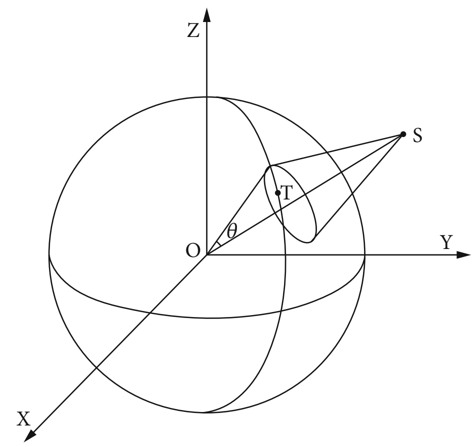

Figure 2: Schematic diagram of single satellite's ground coverage.

$$\theta = \arccos\left(\frac{r_e}{r_e + h_s} \bullet \cos\sigma\right) - \sigma_{cw}, \tag{6}$$

where r_e is the radius of the Earth and h_s is the height of the constellation relative to the ground. Taking the semigeocentric angle θ into the formula for the area of a circle on the Earth's surface, the expression for the spherical crown-shaped area covered by a single satellite to the Earth A_s can be found as

$$A_s = 4\pi r_e^2 \sin^2\left(\frac{\sin\theta}{2}\right). \tag{7}$$

In order to better reflect the nonuniformity of the global distribution of users, the total area A of the area covered by the constellation can also take into account the effect of

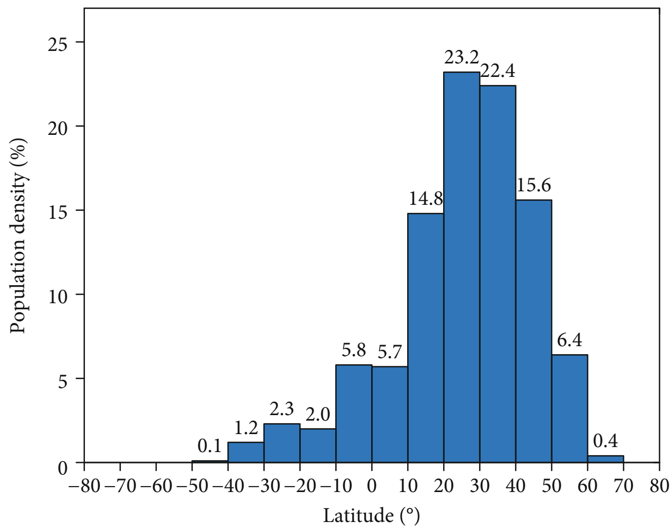

Figure 3: Distribution map of population density with latitude.

Table 1: Typical constellation configuration distribution table.

Constellation	Number of satellites	Planes	Inclination (°)	Altitude (km)
Telesat	351	27	98.98	1015
	1320	40	50.88	1325
OneWeb	1764	36	87.9	1200
	2304	32	55	1200
	2304	32	40	1200
Starlink	1584	72	53.2	540
	1584	72	53	550
	348	6	97.6	560
	172	4	97.6	560
	720	36	70	570

population weighting, using the integration method to obtain the following expression [14]:

$$A_{ew} = \int_{\varphi_s}^{\varphi_n} 2\pi r_e^2 \cos \varphi \mathrm{d}\varphi, \quad (8)$$

where φ_n and φ_s are the upper and lower limits of the integration over latitude, respectively. As a result, the standard number of satellites required for the minimum number of satellites n_s is

$$n_s = \frac{A_{ew}}{A_s}. \quad (9)$$

The coverage efficiency indicator I_{utr} for the constellation can be defined as

$$I_{utr} = \frac{n_s}{n}. \quad (10)$$

In the coverage efficiency indicators for constellations, the combination of parameters such as the number of different satellites, different orbital altitudes, and different orbital inclinations, together with the minimum observation elevation angle of the constellation and the number of visible satellites, allows for a uniform assessment of low-orbiting large-scale communication satellite constellations in terms of configuration assessment.

4. Simulation Analysis

Currently, all major spacefaring nations are conducting research on low-orbit large-scale communication satellite constellations, and the more typical ones are Telesat, OneWeb, and Starlink constellations. Compared with the initial plan, all three have made some changes to the constellation configuration in the first phase, and the constellation configuration distribution is shown in Table 1[21, 22].

As can be seen from Table 1, the Telesat constellation consists of two sets of orbital planes with different inclination angles, with the near-polar orbit ensuring global coverage and the inclined orbit enhancing coverage performance at low latitudes; the OneWeb constellation adds two sets of inclined orbits on top of one set of near-polar orbits, in which a set of orbital planes with an inclination angle of 40° is adopted to enhance coverage performance at low latitudes. Five groups of orbital planes are mainly composed of three different inclination orbital planes. Unlike the first two constellation systems, the orbital altitude is relatively low, with 11.8% of the number of satellites in near-polar orbit, which is lower than the 21% of the Telesat constellation and 27.7% of the OneWeb constellation, making the coverage more concentrated in the middle and low latitudes. Similarly, all three constellations reduce the distribution of satellites at both levels, allowing more satellites to be distributed in densely populated mid- and low-latitude regions. Assuming that the groups of orbital planes and the satellites on each orbital plane of the Telesat, OneWeb, and Starlink

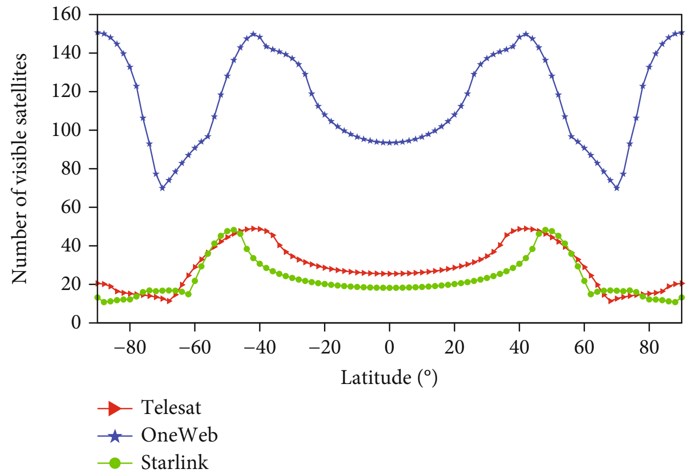

Figure 4: The number of visible satellites in a typical constellation (25° elevation angle).

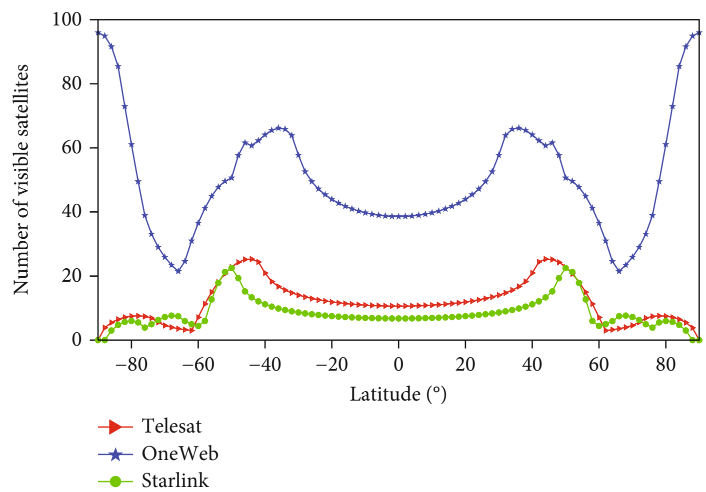

Figure 5: The number of visible satellites in a typical constellation (40° elevation angle).

Table 2: Typical constellation configuration distribution table.

Constellation	Telesat	OneWeb	Starlink
Number of visible satellites (25° elevation angle)	33.90	115.64	25.06
Number of visible satellites (40° elevation angle)	12.68	47.06	8.01

constellations are uniformly distributed, the results of the number of visible satellites for the three constellations are shown in Figures 4 and 5 for 25° ground user observation elevation angle and 40° ground user observation elevation angle, respectively.

Many constellation systems use the user observation elevation angle of 25° as the standard to ensure the quality of constellation communication. As can be seen from Figure 4, the number of visible satellites at high latitudes is relatively similar for the Telesat and Starlink constellations at 25° elevation angle and slightly higher for the Telesat constellation near low latitudes. Compared to these two constellations, the OneWeb constellation has a significantly higher number of visible satellites at 25° elevation than the previous two, but the values fluctuate considerably. The peak number of visible satellites for all three constellations is between 35° and 55° latitude, which basically matches the latitudinal distribution of dense population and provides better coverage performance in densely populated areas.

At a user observation elevation angle of 40°, the communication quality of the constellation can be better improved. Compared with the 25° observation elevation angle, the number of visible satellites in both Telesat and Starlink constellations decreases, and the curve shape of the values does

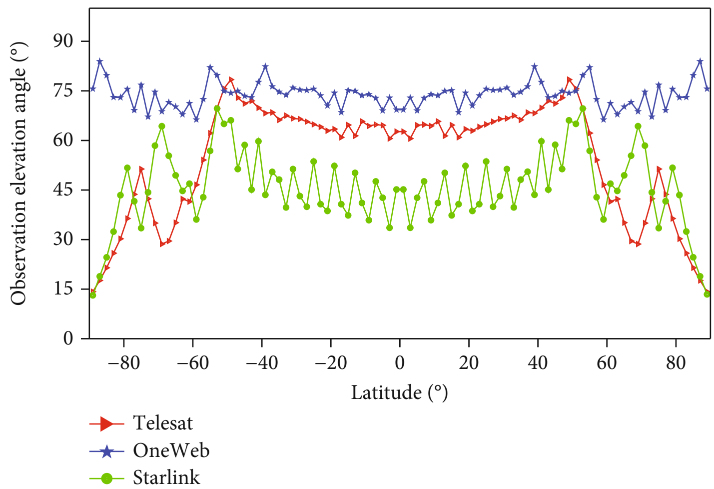

Figure 6: Distribution characteristics of observation elevation angles of typical constellations.

Table 3: Typical constellation performance index parameters.

Constellation	Telesat	OneWeb	Starlink
Minimum average observation elevation angle (°)	65.925	74.400	46.769
Coverage efficiency	60.70%	43.38%	23.17%

not change significantly and remains relatively similar. The OneWeb constellation still has a relatively high number of visible satellites at high latitudes while the values decrease, which may be related to the relatively high proportion of near-polar orbit satellites in the OneWeb constellation. Using equation (9), the average number of visible satellites on the Earth's surface at 25- and 40-degree observation elevation angles can be obtained as represented in Table 2. As can be seen from Table 2, the average number of visible satellites is relatively high for all three constellations, and the coverage performance of the constellation is relatively good, and the average number of visible satellites for OneWeb at 25° observation elevation angle can over reach more than 100 satellites.

In the analysis of the coverage performance of the constellation, the number of visible satellites reflects more the performance characteristics of the coverage weight of the constellation, while the observation elevation angle reflects the communication performance index characteristics of the communication satellite constellation. For a certain latitude on the earth's surface, the observation elevation angle of all grid points at this latitude is obtained by equation (3), and the minimum value is the minimum observation elevation angle at this latitude. The distribution of the minimum observation elevation angle with latitude can be obtained by calculating different latitudes as shown in Figure 6.

From Figure 6, it can be seen that the minimum observation elevation angle distribution of OneWeb constellation is relatively high overall, with most of the values distributed between 70° and 80°, which may be related to the orbital altitude of the constellation and the large number of satellites. The Telesat constellation has no more than 2,000 satellites and can guarantee a minimum observation elevation angle between 60° and 70° at low and medium latitudes, which is close to that of OneWeb, but the minimum observation elevation angle at high latitudes is lower and the communication performance is poorer. The average minimum observation elevation angle under latitude weighting can be obtained by using equation (10). And the coverage efficiency of each constellation to achieve the same coverage performance is obtained by the average observation elevation angle and equations (6) to (10) as shown in Table 3.

As shown in Table 3, the lowest average observation elevation angle of the Starlink constellation is above 40°, which ensures high communication quality, but the constellation coverage efficiency is low, and there are more wasted coverage resources. The constellation coverage efficiency of Telesat constellation reaches 60% and has a better constellation configuration distribution.

In the comparison of simulation results, the orbital altitude of the Starlink constellation is lower compared to that of the other two constellations, and the coverage performance indicators of the constellation are lower for larger constellation sizes. The OneWeb constellation has the highest number of visible satellites and the lowest average latitude elevation angle of the three, and the coverage efficiency is also higher. The Telesat constellation is the smallest among the three, with a slightly higher number of visible satellites and a higher average latitude minimum elevation angle than the Starlink constellation, and the constellation has the best performance in terms of coverage efficiency, and the Telesat constellation has a more reasonable configuration.

5. Conclusion

This paper addresses the performance evaluation of low-orbit large-scale communication satellite constellations and proposes an evaluation model for the constellation configuration performance, mainly studying the spatial location of the constellation and other aspects. Compared with the previous evaluation models, this paper focuses more on the characteristics of a large number of satellites, low orbital altitude, and round-the-clock uninterrupted coverage of the low-orbit large-scale constellation; considering the law of the distribution of performance parameters with latitude and combining the influence of population distribution at different latitudes, this paper proposes a population-latitude weighted evaluation method to establish the evaluation model, replacing the average minimum observation elevation angle of the constellation with the average minimum observation elevation angle under the population distribution, which is more accurate. The performance parameters of the constellation are evaluated more accurately by replacing the mean minimum observation elevation angle of the constellation with the population distribution. The simulation of three typical constellations shows that the evaluation model proposed in this paper can be applied to the configuration evaluation of different kinds of LEO mass communication satellite constellations and can compare their characteristics, which can provide reference for the construction and performance evaluation of LEO mass communication satellites in the future. The next step is to model and analyze the mission performance or communication performance of the constellation on the basis of the constellation configuration performance.

Data Availability

The data used to support the findings of this study are available from the first author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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