Wang, K. and Yang, X. and El-Mowafy, A. 2022. Visibility of LEO satellites under different ground network distributions. In: Institute of Navigation ION GNSS+ 2022, 19-23 September 2022, Denver, Colorado.

Visibility of LEO Satellites under Different Ground Network Distributions

Kan Wang, National Time Service Center, Chinese Academy of Sciences, Xi'an, China; National Time Service Center, Chinese Academy of Sciences, Xi'an, China

Xuhai Yang, National Time Service Center, Chinese Academy of Sciences, Xi'an, China; National Time Service Center, Chinese Academy of Sciences, Xi'an, China Abmed El Mounfy, School of Farth, and Planatery Sciences, Curtin University, Barth, Australia

Ahmed El-Mowafy, School of Earth and Planetary Sciences, Curtin University, Perth, Australia

Biographies

Kan Wang is a Professor at the National Time Service Center, Chinese Academy of Sciences. She received her PhD in GNSS advanced modeling from ETH Zurich in 2016. Her research interests include high-precision GNSS positioning, LEO precise orbit determination and clock determination, LEO-augmented PNT service, and integrity monitoring.

Xuhai Yang is a Professor at the National Time Service Center, Chinese Academy of Sciences. Since 2007, he has served as the director of the research department of high-precision time transfer and precise orbit determination. He is the author of 2 books, more than 30 papers and several patents. His research interests include high-precision time transfer, orbit measurement, orbit determination. Ahmed El-Mowafy is a Professor of Positioning and Navigation, leader of the GNSS research group, and Director of Graduate Research, School of Earth and Planetary Sciences, Curtin University, Australia. He obtained his Ph.D. from the University of Calgary, Canada, in 1995. He has more than 200 publications in precise positioning and navigation using GNSS, quality control, POD, integrity monitoring and estimation theory.

Abstract

The Low Earth Orbit (LEO) satellites have shown various benefits in augmenting the Positioning, Navigation and Timing (PNT) service based on Global Navigation Satellite Systems (GNSSs). The higher number of LEO satellites and their much smaller footprints than those of the GNSS satellites motivate studies of the ground tracking network design to pursue higher visibilities to LEO satellites. This contribution proposes an algorithm, called here 'MaxVis' to select network stations for LEO satellites of different inclinations and altitudes. The goal is to increase the general visibility and shorten the visibility gaps of LEO satellite. A parameter can be set to balance the priority of the two objectives. It was found that LEO satellites with high altitudes and low inclinations tend to deliver high visibility. With only the polar regions excluded from the design area for demonstration purposes, the general visibility could reach above 98% with less than 30 stations when the LEO satellite has an altitude of 1200 km and an inclination of 50 degrees. The visibility could be significantly reduced when island areas are excluded from the design area.

1. INTRODUCTION

Compared with the satellites from the Global Navigation Satellite Systems (GNSSs), which fly at Medium Earth Orbits (MEOs) or even Geosynchronous Orbits (GEOs), the Low Earth Orbit (LEO) satellites have shown various advantages due to their much lower orbital heights, i.e., from hundreds of kilometers to 1500 km (Montenbruck & Gill, 2000). The LEO satellites have lower costs, reduced signal latencies (Garrity & Husar, 2021), and a much stronger signal strength that allows for more robust and penetrating signal transmission (Lawrence et al., 2017). Its fast speed delivers a rapid satellite geometry change, which is very beneficial to shortening the convergence time of the Precise Point Positioning (PPP) (Ge et al., 2018; Li et al., 2018). The multipath effects, which are difficult to model in complicated and kinematic measurement environments and bias the positioning solutions, can also be whitened for LEO satellite signals (Faragher & Ziebart, 2020). These benefits have motivated various studies related to implementing LEO satellites into the high-precision positioning and navigation processes (Reid et al., 2018; Wang et al., 2018), which traditionally mainly considered GNSS satellites with much higher altitudes. LEO augmentation constellations have also been designed to balance between different measures, e.g., the satellite visibility, the measurement geometry and the orbital altitude (Han et al., 2020).

The lower orbital heights of LEO satellites, however, also result in a much smaller satellite footprint compared to the GNSS satellites. As mentioned in (Cakaj et al., 2014), for elevation cut-off angles of, e.g., 4 degrees, the LEO satellites from 600 to 1200 km have a coverage area of only 3.05% to 6.22% of the Earth's surface. Depending on the altitude, the visible time span of an LEO satellite amounts only to 5 to 20 min (Perez, 1998). For applications that need to continuously downlink high-capacity data or high-resolution images from LEO satellites to ground stations, this implicitly requires a high-density ground network to guarantee at least the continuous tracking of the satellite signals. Users in remote areas or on the ocean might need to wait for the following downlink when the LEO satellite becomes visible again to the ground network, resulting in a latency of a few hours (Wang & El-Mowafy, 2020). In Yang et al., (2020), LEO satellite clocks were estimated using simulated signals transmitted to ground stations, where the regional network has led to interruptions in the data and results due to the incontinuous data tracking. In Wang & El-Mowafy, (2021), LEO satellite clock estimates in GRACE Follow-on and Sentinel-3B satellites were found to be disturbed by significant long-term systematic effects related to external influences. Together with the complicated relativistic effects (Larson et al., 2007), the LEO satellite clock prediction degrades quickly with the prediction time, which makes satellite visibility and data latency important factors to reduce latency in the satellite clock products. Investigations were also performed to deal with outages and gaps in LEO satellite clocks (Wang et al., 2022).

Efficient signal transmission methods between LEO satellites and ground stations have been studied for different LEO constellations and from different points of view. The Starlink orbits were evaluated from the ground station's point of view, which were used to confirm the handover process between different satellites (Cakaj, 2021). In Liu et al., (2019), iterative ground station deployment was developed based on marginal revenue maximization, which is used to optimize the system's throughput. To enable efficient data downlinks, advanced data delivery algorithms were designed to allow for proper selection of the downlink station based on geographically distributed ground networks (Lai et al., 2021; Vasisht et al., 2021). Distributions of optical ground stations were optimized to balance between the latency, availability and cost considering the cloud influences (de Portillo et al., 2017).

In this study, within a specific design area, the ground network is designed with an algorithm named MaxVis to pursue two goals, the first is toincrease the general visibility, and the second is to reduce the large visibility gaps of the ground network to a circularorbit LEO satellite of a given inclination and altitude. Under an assumed number of ground network stations, the visibility status is assessed for LEO satellites of different altitudes and inclinations. Here a LEO satellite is considered visible if it can be observed by any of the ground stations above a pre-defined elevation cut-off angle, and the visibility is assessed with regards to the entire network, i.e., considering the connections in the visibilities between stations.

The paper starts with discussing the ground tracks for LEO satellites of different altitudes and inclinations. It is followed by the description of the goals for distributing the network stations. Next, the strategy of the network design, i.e., the MaxVis algorithm, is described. The test results are shown subsequently, showing the designed network for specific LEO satellite orbits and discussing the visibility status for LEO satellites of different inclinations and altitudes. The conclusion is given at the end.

2. GROUND TRACK OF CIRCULAR LEO SATELLITES ORBITS

In this study, the satellite visibility is considered from a ground network to LEO satellites with specific orbital characteristics and over a certain period. The satellite orbital positions can be described by the six Keplerian elements, the semi-major axis a_s , the eccentricity e (zero here), the inclination I, the right ascension of the ascending node Ω , the argument of perigee ω , and the mean anomaly at the initial time M_0 . In this contribution, circular orbits are considered for all the tests, i.e., with e = 0, and with $\omega = 0^\circ$. The ground tracks of LEO satellite orbits with an altitude a of 500 km are illustrated in the left panel of Figure 1 over one day. The blue and red dots represent the orbits with an inclination of 50 and 80 degrees, respectively. In this example, the Ω and M_0 are set to zeros. The rotation matrix from the Earth-Centered Inertial (ECI) system J2000.0 to the Earth-Centered Earth-Fixed (ECEF) system IGS14 is used for the day December 1, 2019, for plotting the ground tracks. In the right panel, the orbital altitudes are set to 400 and 1000 km, with the inclination set to 50 degrees.



One-day Ground Tracks of Circular LEO Satellite Orbits with (left) Different Inclinations and (right) Different Altitudes. Ω and M_0 are Set to Zeros

From the left panel of Figure 1, it can be observed that different inclinations mainly influence the latitude range and the form of the ground tracks. At the same time, as shown in the right panel of Figure 1, different altitudes lead to different satellite velocities, which influences the longitude span between adjacent orbital rounds. Also, the altitude of the LEO satellite affects its footprint on the Earth and the length of time span that a ground station can observe the satellite. As such, for the same ground network, these two parameters have significant impacts on satellite visibility.

When changing Ω and M_0 , ground tracks are shifted in the longitude direction as shown in Figure 2, while the form of the ground tracks is not changed. The altitude and the inclination are set to 1000 km and 50 degrees, respectively. The shifting of the ground tracks in the longitude direction can also be achieved by extending the test period. Figure 3 shows the ground tracks over seven and 14 days with both the Ω and M_0 set to zeros. The rotation matrices from the ECI to the EFTF from December 1 to 7 and from December 1 to 14, 2019, were used for the system transformation. From Figure 2 and Figure 3 it can be observed that the effects of changing Ω and M_0 can be achieved by shifting the test time window. Increasing the test period will increase the density of the ground tracks within this period, which covers more situations of shifting in the longitude direction. As such, in this study, circular LEO satellite orbits are only distinguished with different inclinations and altitudes. 14-day ground tracks from December 1 to 14, 2019, which provide a rather good density as shown in the right panel of Figure 3, are used to assess the satellite visibility.

One-day Ground Tracks of Circular LEO Satellite Orbits with (left) Different Right Ascension of the Ascending Node Ω and (right) Different Mean Anomaly at the Initial Time M_0 . The Altitude is Set to 1000 km, and the Inclination is Set to 50 degrees



Figure 3

Seven-day (left) and 14-day (right) Ground Tracks of LEO Satellite Orbits with the Right Ascension of the Ascending Node Ω and the Mean Anomaly at the Initial Time M_0 Set to Zeros. The Altitude is Set to 1000 km, and the Inclination is Set to 50 degrees



3. GOALS

The cost for building and maintaining the ground infrastructure to receive and process the LEO satellite signals is usually pre-defined and needs to be carefully studied for different locations by the network designers. In this section, the problem is formulated for networks of a fixed number of ground stations to be selected, denoted as N. The ground stations are assumed to be globally distributed, but only on land. It is possible to exclude certain areas due to the high cost and difficulties in building and maintaining the stations, e.g., in the polar regions, or for safety and political reasons. Within the allowed land-based areas, denoted as "the design area" in this study, the following goals are aimed for LEO satellite with the altitude a and the inclination I: \triangleright Goal A: Increase the general probability of visibility for the satellite, denoted as P_v with:

$$P_{\rm v} = \frac{T_{\rm v}(\theta)}{T_{\rm all}} \tag{1}$$

where T_{all} represents the entire test period, i.e., 14 days in this study. $T_v(\theta)$ stands for the period that the satellite is visible to at least one ground station over an elevation cut-off angle of θ degrees, which is defined as 5 degrees in this contribution.

Solution Goal B: Shorten long visibility gaps of the satellites. A visibility gap, denoted as T_{gap} , is defined as a time interval within the test period, during which the satellite cannot be observed by any ground station above the elevation cut-off angle. To possibly break long visibility gaps, instead of simply summing all the gap lengths, the square root of the squared sum of all gap lengths, denoted as \overline{T}_{gap} , is shortened. \overline{T}_{gap} can be expressed as:

$$\bar{T}_{\text{gap}} = \sqrt{\sum_{i=1}^{k} T_{\text{gap},i}^2}$$
(2)

where k is the number of gaps within the test period. In this way, long gaps with large $T_{gap,i}^2$ tend to be broken into small pieces by the algorithm.

The two goals mentioned above are both considered in the network design, with Goal A set as the primary goal, and Goal B set as the secondary goal. In the next section, the algorithm for network design is described in detail.

4. ALGORITHM FOR NETWORK DESIGN: MAXVIS

As mentioned in the last section, certain areas could be excluded before distributing the ground network, e.g., areas with political instabilities, remote areas like desert, snow mountain, depopulated zone that cannot be easily reached, and areas that cannot be used to build stations due to other political reasons. All the relevant factors need to be carefully studied and considered by the network designers before defining the appropriate design area. In this study, for demonstration of the proposed algorithm, only the pole regions and ocean areas are excluded for the reason of cost and technical difficulties. It is also noted that the topography of the land is not considered in this contribution, which means that the station location is described with the latitude, longitude and a height of zero. This could lead to slight deviations in the elevation angle to the LEO satellite, but generally within 0.5 degrees.

The algorithm to select the network stations is named here as MaxVis, and is performed with three steps:

Step 1: Find candidate stations

The world map is first transformed into a raster map with the same length (in degrees) in the latitude and longitude, filled with value 0 for land, 1 for coast and 2 for ocean. The resolution of the raster map needs to be pre-defined, which is set to 0.1 degrees in this study. The Earth is distributed into grids with the latitude and the longitude span of M degrees. The grids outside of the design area are excluded. Each grid is then searched with a pre-defined search resolution, in this study 0.1 degrees. The grids that do not include any land areas (value 0) are excluded as well. As an example, Figure 4 shows the valid grids with a grid length of 5 degrees. There are in total 971 grids found within the design area.



Valid Grids and Candidates within the Land-based Design Area

After distributing the design area into grids, the grid center is selected as the candidate for the network locations. If the center point is on the ocean or considered as coast (value 1), the search process begins with a resolution of 0.1 degrees. The valid searched point within the land area nearest to the grid center will be selected as the candidate for the corresponding grid. The candidates are illustrated with magenta dots in Figure 4.

Step 2: Select main stations

As mentioned in the last section, to achieve the two goals, the ground network is designed to i) increase the general visibility of the LEO satellite and ii) decrease large visibility gaps. The procedure to select the main network stations is described as follows:

- 1. For each of the candidate stations (see Step 1), compute its visible time to the LEO satellite (with a given altitude *a* and inclination *I*, and with *e*, Ω , M_0 and ω set to zeros) over the test period (December 1 to 14, 2019) above the pre-defined elevation cut-off angle.
- 2. Find the longest visible time $\max(T_{v,1})$. For candidates having the visible time not shorter than $(\max(T_{v,1}) p)$, the one that delivers the shortest \overline{T}_{gap} (see Equation 2) is selected as main station 1. The period *p* characterizes the priority of Goal A over Goal B.
- 3. With the visible time of main station 1 excluded, find the candidate having the longest visible time in the remaining period, denoted as $\max(T_{v,2})$. For candidates having the visible time not shorter than $(\max(T_{v,2}) p)$, the one that delivers the shortest \overline{T}_{gap} (see Equation 2) is selected as main station 2.
- 4. Continue the station selection with the procedure mentioned above. If the station number N is reached, the search process stops. If the visible time to the LEO satellite can not increased by adding new stations anymore before the station number N is reached, e.g., at number N k, the remaining k stations are considered as backup stations and are selected as described in Step 3.

Step 3: Select backup stations

As described in Step 2, the total station number N could be larger than the station number needed to reach the highest probability of visibility. In such a case, the remaining stations are used to backup possible malfunction of important main stations. They are selected as follows:

1. For each of the main stations, the summed gap length that is caused by its malfunction is calculated. The largest gap length is denoted as $\max(T_{\text{mal},1})$.

- 2. For main stations that cause gaps not shorter than $(\max(T_{\text{mal},1}) p)$ of a possible malfunction, the one that delivers the largest $\overline{T}_{\text{gap}}$ is denoted as high-importance main station 1. The remaining candidate that could fill this gap to the largest extent is selected as the first backup station.
- 3. Repeat procedures 1) and 2) for other problem main stations.
- 4. The search process continues until the remaining k backup stations are all selected. In case that all main stations are backed up before the station number N is reached, the procedure is repeated for malfunction of both the main stations and their backup stations, i.e., in 2), the candidate that could fill the gap to the second-largest extent is selected.

In summary, the search procedure first attempts to achieve as much visible time to the LEO satellite as possible, and then tries to shorten large visibility gaps. If the maximal visibility can be achieved before the planned station number N is reached, the remaining stations are used to back up the main stations in case they become unavailable. The backup stations are aimed to increase the visibility within the gap caused by the malfunction of the main stations.

5. TEST RESULTS

In this section, the test results are discussed for the two goals introduced in Section 3, using the network design as described in the last section. The number of the network station is set to 120. The tested altitude of the LEO satellite ranges from 400 to 1200 km, and the inclination varies from 30 to 89 degrees. The right ascension of the ascending node Ω and the mean anomaly at the initial time M_0 are set to zeros, and the transformation matrices from December 1 to 14, 2019, are used to transform the orbits from the Earth-centered initial (ECI) system to the ECEF. The visible time is computed with a sampling interval of 30 s.

5.1. Visibility and Gaps

As an example, for the time points at 0 s and 990 s on December 1, 2019, the visible candidate stations are illustrated with green dots in Figure 5 for the near-polar LEO orbit with an altitude of 490 km and an inclination of 89 degrees. As shown in Figure 5, when the LEO satellite flies over high latitudes, more candidate stations are visible to the satellite. This is related to the high inclination of the tested LEO satellite and the fact that the grids with the same length in degrees cover smaller areas in high latitudes than in low latitudes.

Figure 5

Visible Candidate Stations (Green Dots) at Two Different Time Points for the LEO Satellite with an Altitude of 490 km and an Inclination of 89 degrees



Using the test LEO satellite as mentioned above, to achieve our goals, the ground network is distributed as shown in Figure 6 with the total station number N set to 120, and with p set to 1 min. The magenta to yellow stars denote the selected network stations

with the order illustrated by the color bar. The magenta stars, e.g., denote the stations that are selected with high priority due to their great importance in geometry. The visible time does not increase when 103 network stations are selected. The other 17 stations, shown with blue dots, serve as backup stations. From Figure 6 it can be observed that it is important to have some network stations at high-latitude areas, while their number does not need to be high. At coastlines, the orange to yellow stations do not increase the visibility a lot, which means that they could be removed when the number of stations is decreased.

Figure 6

Ground Network for LEO Satellite with an Altitude of 490 km and an Inclination of 89 degrees



Figure 7 illustrates the variation of the visibility and the largest gap length with the station numbers. It can be observed that increasing the main stations from 60 to 103 only increases the visibility from about 74.5% to 75.4%. This indicates that if the station number N decreases to 60, the general visibility is not significantly influenced. This, however, would harm the redundancy of the network. At the same time, as shown by the orange line in Figure 7, the largest gap length quickly shrinks to 47.5 min with 23 stations, and finally to 39 min with 78 stations. The further increase in the visibility and reduction in the largest gap length are limited by the design area used.

Figure 7

Variation of the Visibility and the Largest Gap Length with the Station Numbers for LEO Satellite with an Altitude of 490 km and an Inclination of 89 degrees



When increasing the period p, the algorithm tends to break large visibility gaps with fewer stations. The left panel of Figure 8 shows the variations of the largest gap length with the station numbers for different values of p, and the right panel of Figure 8 shows the variations of the term $\overline{T}_{gap}/T_{all}$ with the station numbers for different values of p. \overline{T}_{gap} is calculated with Equation (2), and recall that T_{all} denotes the length of the entire test period, i.e., 14 days here. It can be observed that a large value of p sets higher priority for Goal B, i.e., shortening large visibility gaps. The largest gap, e.g., is broken into short pieces with fewer stations (see the green lines in the left panel of Figure 8). This, however, generally slows down the speed in achieving Goal A. The station number needed to reach a probability of visibility of, e.g., 75% increased from 71 to 79 when increasing p from 60 to 3600 s. The differences caused by p are generally not significant for both cases, i.e., in achieving Goal A and B.

Figure 8

The Variations of (left) the Largest Gap Length and (right) the Term $\overline{T}_{gap}/T_{all}$ (see Equation 2) with the Station Numbers for Different Values of p. The Test LEO Satellite has an Altitude of 490 km and an Inclination of 89 degrees



5.2. Visibility status for LEO satellites of different inclinations and altitudes

As discussed for Figure 1, different inclinations and altitudes of the LEO satellites result in differences in satellite visibility. In this section, the visibility status is compared for LEO satellites with different inclinations and altitudes. The details for calculation are mentioned at the beginning of Section 5. The period p is assumed as 60 s in the search algorithm. The number of main stations is limited by N of 120.

Figure 9 shows the probability of visibility (P_v with Equation 1) of LEO satellites with different altitudes and inclinations. The left panel of Figure 9 illustrates the P_v for a LEO satellite with an altitude of 500 km and inclinations varying from 30 to 89 degrees. It can be observed that under the same altitude, a lower inclination tends to deliver a higher probability of visibility. To achieve the same probability of visibility, satellite with a lower inclination tends to require a smaller number of ground stations except for very low P_v (see the beginning phase at the left panel of Figure 9). This applies also to satellites with other altitudes from 400 to 1200 km. The differences in P_v is related to the different forms of the ground tracks caused by satellite altitudes (see the left panel of Figure 1) and the different land-to-ocean ratios in various latitude bands. The areas beyond the latitude of -50 degrees are mainly occupied with ocean and pole regions, which are almost excluded from the design area. This is not beneficial for achieving a high P_v .

Probability of Visibility for LEO Satellite with (left) an Altitude of 500 km with Different Inclination Angles, from 30° to 90°, and (right) an Inclination of 50 degrees but with Different Altitudes from 400 to 1200 km



The right panel of Figure 9 illustrates the probability of visibility for the LEO satellite with an inclination of 50 degrees and altitudes varying from 400 to 1200 km. It can be seen that under the same inclination, a high altitude of LEO satellites is beneficial for achieving a high P_v . To achieve the same P_v , a lower number of ground stations is required for higher orbits. These conclusions also apply for LEO satellites with other inclinations varying from 30 to 89 degrees. As an example, having an inclination of 50 degrees and an altitude of 1200 km (see the gray line in the right panel of Figure 9), a P_v of 98% can be achieved with 27 main stations (see Figure 10).

Figure 10

Ground Network Distribution with 27 Main Stations to Achieve a Probability of Visibility of 98%. The LEO Satellite has an Altitude of 1200 km and an Inclination of 50 degrees



The probabilities of visibility that can be finally achieved (with the main station number not exceeding 120) are listed in Table 1. The P_v at the left bottom corner with an inclination of 30 degrees and an altitude of 1200 km has reached 98.5%, while the P_v with an inclination of 89 degrees and an altitude of 400 km remains about 70%. In addition to the final P_v that can be achieved, the number of required main stations to achieve the same P_v is significantly different for LEO satellites of different orbital characteristics. As

shown in Table 2, the P_v of 80% can be reached with 11 main stations for LEO satellite with an inclination of 30 degrees and an altitude of 1200 km, while it cannot be reached with 120 stations for LEO satellite with an inclination of 89 degrees and an altitude of 400 km. "-" in Table 2 means that the required probability of visibility is not yet achieved when the main station number reaches 120.

Table 1

Probability of Visibility that can be Achieved with the Main Station Number not Exceeding 120

Altitude (km)	Inclination (degree)				
	30	50	70	89	
400	79.4%	80.8%	74.9%	71.5%	
600	88.7%	90.3%	84.1%	79.1%	
800	93.9%	94.5%	90.3%	84.2%	
1000	97.1%	96.8%	94.6%	87.8%	
1200	98.5%	98.2%	97.2%	90.8%	

Table 2

The Numbers of Main Stations Required to Achieve a Probability of Visibility of 60% and 80% (Separated by a Slash Sign)

Altitude (km)	Inclination (degree)				
	30	50	70	89	
400	20/-	28/70	34/-	38/-	
600	13/20	17/28	20/38	22/-	
800	10/15	13/20	14/22	16/29	
1000	9/13	10/16	11/18	12/21	
1200	7/11	9/14	9/15	10/17	

It is worth noting that the results obtained above could be optimistic, as the current design area has included almost all land-based regions (except for the pole regions) for the purpose of demonstration. In practice, network designers may need to exclude other regions from the design area, leading to a worse visibility under the same number of ground stations. For example, when excluding the candidate stations on the islands circled in green as shown in Figure 11, the probability of visibility suffered a decrease of about 5% to 8% for all the four tested altitude-inclination combinations as shown in Figure 12 (see the dashed lines).

Valid Grids and Candidate Stations Within the Land-based Design Area. The Island Candidate Station Locations Shown in Green Circles are Excluded from the Design Area as an Example



Figure 12

Probability of Visibility for Different LEO Satellite Orbits Including the Green-circled Candidates in Error! Reference source not found. (Solid Lines) and Excluding them (Dashed Lines)



6. CONCLUSIONS

The mega-constellation LEO satellites have shown significant benefits in augmenting GNSS-based Positioning, Navigation and Timing (PNT) service. This contribution proposed an algorithm, called MaxVis, for ground network distribution, aiming to increase the probability of visibility and reduce large visibility gaps in observing LEO satellites of different inclinations and altitudes. The visibility is considered for the entire network, and a parameter period p can be set to balance the two goals.

With almost all the land-based areas considered as the design area, i.e., excluding only the polar regions, the network stations are selected with different priorities from candidate sites located in pre-defined grids. With p set to a small value of 60 s to achieve mainly the first goal of maximizing the visibility, it was found that the highest visibility that can be achieved is related to both the satellite inclination and altitude. A low inclination and a high altitude tend to deliver high visibility under the same station number.

Using 14 days of the ground tracks from simulated circular orbits of different characteristics, with the station number not exceeding 120, the visibility has reached above 98% for LEO satellites with an altitude of 1200 km and an inclination below 50 degrees, while it remains about 70% for near-polar orbits with an altitude of 400 km. To reach the same visibility, the required station number is also quite different for different orbits. For orbits with an inclination of 30 degrees and an altitude of 1200 km, only 11 stations are needed to reach 80% visibility while near-polar orbits with an altitude of 400 km cannot reach this visibility level with even 120 stations. The geometry of the design area for the network selection is an essential information to the final visibility that can be reached. This needs to be carefully defined by different network designers considering various issues. With certain areas excluded from the design area, the visibility could be significantly reduced.

The proposed algorithm that can help in designing the monitoring network currently considers only circular LEO satellite orbits with a given altitude and inclination at each time. As an LEO constellation may combine satellites with different inclinations and altitudes, our further work will extend the algorithm for this case in an integrated solution, with proper weights set to different orbital types within one LEO constellation.

ACKNOWLEDGMENTS

This work is funded by the National Time Service Center, Chinese Academy of Sciences (CAS) (No. E167SC14), the CAS "Light of West China" Program (No. XAB2018YDYL01), and the National Natural Science Foundation of China (No. 12073034). We acknowledge also the support of the international GNSS monitoring and assessment system (iGMAS) at the National Time Service Center, and the National Space Science Data Center, National Science & Technology Infrastructure of China (http://www.nssdc.ac.cn).

REFERENCES

Cakaj, S. (2021). The Parameters Comparison of the "Starlink" LEO Satellites Constellation for Different Orbital Shells. *Frontiers in Communications and Networks*, 2, 643095. https://doi.org/10.3389/frcmn.2021.643095

Cakaj, S., Kamo, B., Lala, A., & Rakipi, A. (2014). The Coverage Analysis for Low Earth Orbiting Satellites at Low Elevation. *International Journal of Advanced Computer Science and Applications*, *5*, 6.

der Portillo, I., Sanchez, M., Cameron, B., & Crawley, E. (2017). Optimal Location of Optical Ground Stations to Serve LEO Spacecraft. *Proc. of the 2017 IEEE Aerospace Conference*, Big Sky, MIT, USA. https://doi.org/10.1109/AERO.2017.7943631

Faragher, R., & Ziebart, M. (2020). OneWeb LEO PNT: Progress or Risky Gamble? *Inside GNSS*, September 28, 2020. https://insidegnss.com/oneweb-leo-pnt-progress-or-risky-gamble/

Garrity, J., & Husar, A. (2021). Digital Connectivity and Low Earth Orbit Satellite Constellations: Opportunities for Asia and the Pacific. *ADB Sustainable Development Working Paper Series*, No. 76, April 2021.

Ge, H., Li, B., Ge, M., Zang, N., Nie, L., Shen, Y., & Schuh, H. (2018). Initial assessment of precise point positioning with LEO enhanced global navigation satellite systems (LeGNSS). *Remote Sensing*, *10*(7), 984. https://doi.org/10.3390/rs10070984

Han, Y., Wang, L., Fu, W., Zhou, H., Li, T., Xu, B., & Chen, R. (2020). LEO navigation augmentation constellation design with the multi-objective optimization approaches. *Chinese Journal of Aeronautics*, *34*(4), 265-278. https://doi.org/10.1016/j.cja.2020.09.005

Lai, Z., Wu, Q., Li, H., Lv, M., & Wu, J. (2021). ORBITCAST: Exploiting Mega-Constellations for Low-Latency Earth Observation. *Proc. of the 29th IEEE International Conference on Network Protocols*, Virual.

Larson, K.M., Ashby, N., Hackman, C., & Bertiger, W. (2007). An assessment of relativistic effects for low Earth orbiters: the GRACE satellites. *Metrologia*, 44(6), 484-490. https://doi.org/10.1088/0026-1394/44/6/007

Lawrence, D., Cobb, H. S., Gutt, G., O'Connor, M., Reid, T. G. R., Walter T., & Whelan, D. (2017). Innovation: Navigation from LEO. *GPS World*, June 30, 2017. https://www.gpsworld.com/innovation-navigation-from-leo/

Li, X., Ma, F., Li, X., Lv, H., Bian, L., Jiang, Z., & Zhang, X. (2018). LEO constellation-augmented multi-GNSS for rapid PPP convergence. *Journal of Geodesy*, *93*, 749-764. https://doi.org/10.1007/s00190-018-1195-2

Liu, S., Wu, T., Hu, Y., Xiao, Y., Wang, D., & Liu, L. (2019). Throughput Evaluation and Ground Station Planning for LEO Satellite Constellation Networks. *In: Yu, Q. (eds) Space Information Networks. SINC 2019. Communications in Computer and Information Science*, 1169, Springer, Singapore, 3-15. https://doi.org/10.1007/978-981-15-3442-3_1

Montenbruck, O., & Gill, E. (2000). Around the world in a hundred minutes. *Satellite orbits, 1st ed.*; Springer: Berlin, Heidelberg, Germany, 1–13.

Perez, R. (1998). Introduction to Satellite Systems and Personal Wireless Communications. *Wireless Communications Design Handbook, Vol. 1: Space Inteference, Academic Press*, 1-30. https://doi.org/10.1016/S1874-6101(99)80014-3

Reid, T. G. R., Neish, A. M., Walter, T., & Enge, P. K. (2018). Broadband LEO constellations for navigation. *Navigation, Journal of the Institute of Navigation*, 65(2), 205–220. https://doi.org/10.1002/navi.234

Vasisht, D., Shenoy, J., & Chandra, R. (2021). L2D2: Low Latency Distributed Downlink for Low Earth Orbit Satellites. *Proc. of the 2021 ACM SIGCOMM 2021 Conference*, Vitual, 151-164. https://doi.org/10.1145/3452296.3472932

Wang, K., & El-Mowafy, A. (2020). Proposed orbital products for positioning using mega-constellation LEO satellites. *Sensors*, 20(20), 5806. https://doi.org/10.3390/s20205806

Wang, K., & El-Mowafy, A. (2021). LEO satellite clock analysis and prediction for positioning applications. *Geo-spatial information science*, 25(1), 14-33, https://doi.org/10.1080/10095020.2021.1917310

Wang, K., El-Mowafy, A., & Rizos, C. (2022). Bridging clock gaps in Mega-constellation LEO satellites. *Proc. of the ION ITM* 2022, Long Beach, CA, USA, 881-892. https://doi.org/10.33012/2022.18246

Wang, L., Chen, R., Li, D., Zhang, G., Shen, X., Yu, B., Wu, C., Xie, S., Zhang, P., Li, M., & Pan, Y. (2018). Initial assessment of the LEO based navigation signal augmentation system from Luojia-1A satellite. *Sensors*, *18*(11), 3919. https://doi.org/10.3390/s18113919

Yang, Z., Liu, H., Qian, C., Shu, B., Zhang, L., Xu, X., Zhang, Y., & Lou, Y. (2020). Real-time estimation of low Earth orbit (LEO) satellite clock based on ground tracking stations. *Remote Sensing*, *12*(12), 2050. https://doi.org/10.3390/rs12122050