Low-Earth-Orbiter communication satellites constellation and operation scenario over Korea

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Abstract

For 6G standardization and communication network, each country invests in Low-Earth-orbiter (LEO) communication satellite business. However, there are the threats of signal interference by frequency-band and collision among the satellites in space due to the recent launch of numerous LEO communication satellites such as Starlink, Oneweb, and Kuiper. In particular, the issue of frequency registration for satellite operation and the interference of receiver and transmitter between ground and satellite are studied a lot.

In this study, we calculate an optimized numbers of communication satellites by an analysis for the continuous operation constellation covering Korea and perform some simulations by calculating the numbers of satellites required for the beam coverage according to altitude and orbit inclination. We analyse satellite total numbers, orbit plane, and optimizing parameter for the continuous coverage of communication. The optimization parameter in designing the constellation of communication satellite is dominant by the Earth-centered half cone angle in star pattern and relative phase parameter between satellites in adjacent orbit planes, F, by delta pattern. In the 45-degree inclined orbit at the 888km altitude, using a delta pattern (F=1), at least more than 2 satellites out of 80 satellites are continuously visible over Korea.

Keywords: (Constellation, Beam coverage, Star pattern, Delta pattern, Relative phase)

Nomenclature

R_E	= *Radius of Earth*
R	= *Range from Earth to satellite height*
GM	= *Gravitational constant w.r.t Earth*
h	= *Altitude from surface to satellite*
h'	= *Range of coverage*
el	= *Elevation angle*
θ	= *Beam angle from satellite antenna*
ψ	= *A half cone angle from Earth center*
D_{max}	= *Maximum coverage distance by beam angle*
T	= *Total satellites numbers consisting of constellation*
P	= *Numbers of orbital planes*
S	= *Numbers of satellites per orbit*
F	= *Relative phase parameter between satellites in adjacent planes*
$\dot{\Omega}$	= *Rate of ascension ascending node*
J_2	= *Second order zonal term of gravity perturbation*
e	= *Eccentricity of satellite orbit*
i	= *Inclination of satellite orbit*
a	= *Semi-major axis of satellite orbit*
$\dot{\omega}$	= *Argument of perigee rate*
$\emptyset$	= *Latitude of ground*

1. Introduction

Most communications satellites were known to be located at the geostationary orbit. Recently, numerous low-cost satellites, such as Starlink and One-web, have been placed in low-Earth-orbit to cover the entire Earth and enable to communicate through the LEO satellites. There was an IRIDUM satellite group that enabled mobile communication while covering the entire Earth as a LEO satellite group, which operated with 77 satellites in polar orbit. There was a Globalstar satellite group that consisted of a satellite group with an inclined orbit, which consisted of 48 s atellites with an inclined orbit at the 1,389 km [1].

The Korean Peninsula has a well-established ground mobile communication infrastructure, but satellite communication is an essential element for 3-dimension communication network such as UAM or 3D communication internet even during flight. Service must be provided via satellite for 3-D communication network. However, in designing a satellite constellation, there should be designed for how many satellites and how many satellites are to be placed on the orbital plane according to the range of communication coverage and the orbital characteristics [2]. Most satellite constellation design was used by walker pattern. However, it can be placed in a polar orbit, or there can be a difference in the area covered according to the latitude and minimum elevation angle. The constellation design based on the required mission such as a satellite communication, navigation, or revisit of target for Earth observation is conducted. In this research we focus on the satellite communication using LEO satellites. In Ref. [3], they studied the sensor requirement for global and partial coverage of the Earth. The goal of this study is to design a satellite constellation that can cover over the Korean Peninsula continuously. We study the trade-off of satellite constellation design and related parameters to perform 3D communication network according to the altitude and Earth-centered half cone angle.

2. Satellite constellation design and parameters

Due to the influence of the Earth's gravitational field, the altitude of the satellite decays according to the time. Thus, unsymmetrical gravitational perturbation and drag perturbation by the Earth atmosphere affects to the change of semi-major axis changes. In this case, an orbital maneuver to raise the satellite to a desired altitude must be performed, and mission service may not be supported during the orbital maneuver. However, the change of semi-major axis makes more complicated and difficult satellite constellation.

$$\dot{\Omega} = -\frac{3}{2}\frac{2\pi J_2 \cos i}{(1-e^2)^2}\left\{\frac{R_E}{a}\right\}^2 \qquad (1)$$

$$\dot{\omega} = \frac{3}{4}\frac{2\pi J_2}{(1-e^2)^2}\left\{\frac{R_E}{a}\right\}^{3.5}(5\ \cos^2 i - 1) \qquad (2)$$

As seen in Eq. (1), right ascension ascending node is drifted toward westward if inclination is 90° and less than 90°. As the rate of right ascension ascending node and argument of perigee increases the semi-major is decreased as time goes. In order to perform satellite communication, beam coverage must ensure continuous visibility, and imaging must ensure revisit for a specific area. There are some factors that design satellite constellation such as a field of view, duration, continuity, gaze angle, and location/latitude of interest [1]. In this research we study walker pattern for polar orbit [4] and inclined orbit by theoretical analysis and simulation.

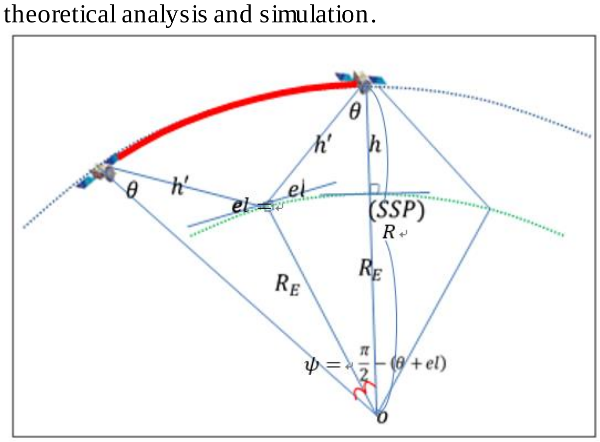

Fig. 1. Geometry for satellite coverage area

The period of satellite revolution is expressed by $Period = 2\pi\sqrt{\frac{(R_E+h)^3}{(GM)}}$

According to the sine's law $\frac{(R_E+h)}{\sin\left(\frac{\pi}{2}+el\right)} = \frac{R_E}{\sin(\theta)}$, the beam coverage angle, θ becomes

$$\theta = \mathrm{asin}\left(\frac{R_E}{(R_E+h)}\cos(el)\right) \qquad (3)$$

In Fig. 1, h' means range of the coverage and expressed by $h' = \frac{h}{\cos\theta}$ and $\mathrm{R} = R_E + h$

The Earth-centered half-cone angle, ψ is defined as

$$\psi = \frac{\pi}{2} - (\theta + el) \qquad (4)$$

At the lowest elevation, the length of circumferences is $2\psi R$.

To obtain the time of coverage at specific position, time is calculated as follows:

$$\mathrm{Time} = \frac{\psi}{\pi}\, Period \qquad (5)$$

The distance maximum coverage is calculated as follows:

$$D_{max} = 2\, R_E\, \psi \qquad (6)$$

2.1 Start Pattern

The star pattern satellite constellation is designed to pass through the polar region and has excellent coverage at high latitudes.

$$\mathrm{T = P\,S} \sim 4\ \cos(\emptyset)/(1 - \cos(\psi)) \qquad (7)$$

$$1.3\mathrm{P} < \mathrm{S}\cos(\emptyset) < 2.2P \qquad (8)$$

Where P is the number of orbit plane, S is the numbers of satellites at each orbit plane, and ψ is the beam coverage at the Earth center as given in Fig. 1. Satellite latitude becomes zero in star pattern case. The altitude is reversely proportional to the center of the Earth coverage.

$$(P-1)\psi + (P+1)\Delta = 180°\ \cos(\emptyset) \qquad (9)$$

$$\Delta = \cos^{-1}\left[\cos\psi / \left(\cos\frac{\pi}{S}\right)\right] \qquad (10)$$

$$\alpha \cong \psi + \Delta, \quad \beta \cong 2\Delta \qquad (11)$$

Here α is the angle between same directional satellites and β is the different directional relative phase angle. When the latitude-angle is 90°, the semi-major axis is related to the satellite's altitude, and the right ascension ascending node is related to the satellite's departure plane. In Fig. 2, the beam coverage angle, θ decreases according to the altitude of satellite. However, the Earth-centered half cone angle increased with respect to the altitude. The lower the elevation is lower the angles are. Figure 2 shows total satellite numbers according to the Earth-centered half-cone angle, ψ. At the altitude of 500 km to 1000 km, the Earth-centered half cone angle has a value less than 30 degrees. In addition, when the latitude is 0, it has a constellation that covers the entire earth, and figures 3 and 4 show the ranges covered by the satellite from each latitude to the polar region. Figure 2 is the relation between the Earth-centered half-cone angle and total satellites by the function of elevation and Fig. 3 shows total satellite numbers according to the latitude. As seen in Fig.3, the Earth-centered half cone angle relates to the function of the elevation angle. As the ψ is smaller, total satellite numbers are increased and the altitude is lower as shown in Figs. 2-4.

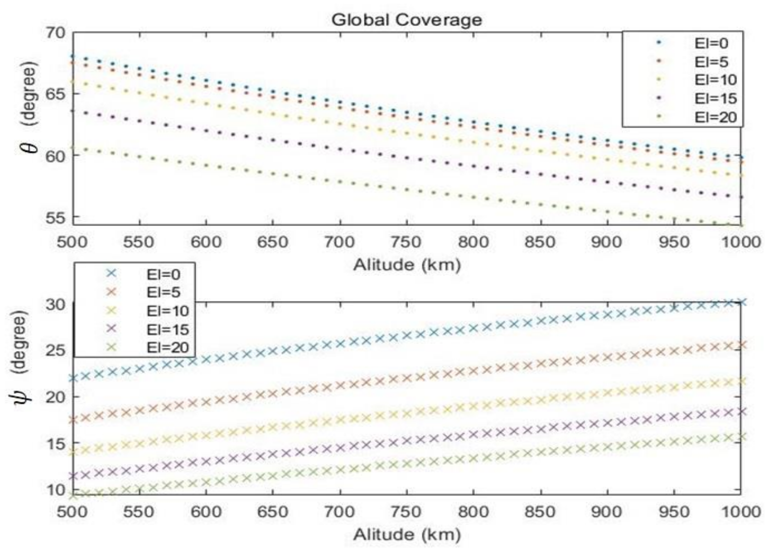

Fig. 2. Earth-centered half cone angle vs. the altitude by elevation

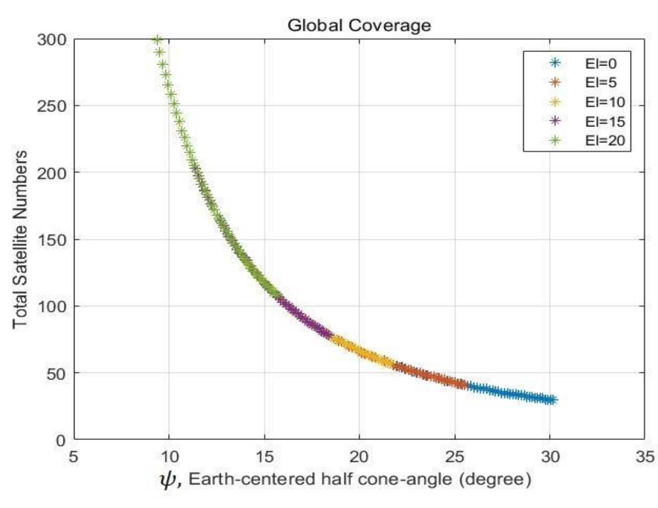

Fig. 3. Total satellite numbers w.r.t Earth-centered half cone angle by elevation

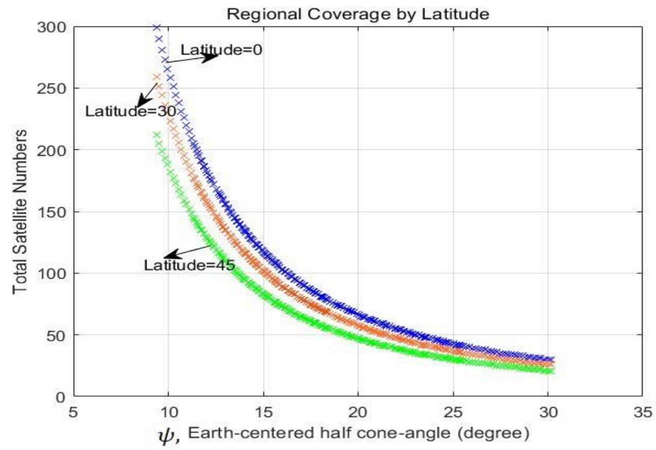

Fig. 4. Total satellite numbers w.r.t Earth-centered half cone angle by latitude

Table 1 shows total satellite numbers, orbital plane, and satellite numbers per orbital plane. As the altitude is lower total satellite numbers to cover over Korea are increased. At the fixed elevation angle, 15-degree, total satellite numbers covering whole Earth are roughly required by 77-112 at 888km altitude and 176 satellites are required at 550 km by above Eqns. analysis.

Table 1. Constellation design by star pattern analysis of single coverage

	H=888km		H=550km	
Minimum elevation (Fixed)	15°	15°	15°	15°
Latitude (∅)	30°	0°	30°	0°
Beam coverage angle (θ)	57.98°	57.98°	62.78°	62.78°
Earth-centered half-cone angle (ψ)	17.02°	17.02°	12.22°	12.22°
Total satellite numbers (T)	63-108	77-112	117-204	135-228
Orbit plane (P)	9,10,11,12	11,12,13,14	12,11,10,10,9	12,11,10,10, 9
Satellite number per orbit plane (S)	9, 8, 7, 7	8, 8, 7, 7	13,14,15,16,17	15,16,17,18,19
α	34.64	34.47	24.65	24.61
β	35.24	34.91	24.86	24.78
Distances	3788.92 km	3788.92 km	2720.78 km	2720.98 km

2.2 Delta Pattern

The delta pattern constellation can reduce the number of satellites compared to the star pattern, but has the disadvantage that it may not be able to cover the polar area. However, the delta pattern is preferred because it can obtain the optimal number of satellites that cover the Korea peninsula well. The delta pattern satellite constellation consists of total satellites, T, Orbital plane, P, with an orbital inclination angle i are arranged at S intervals, and S satellites per orbit plane are arranged at P intervals on the same orbital plane ($S=\frac{T}{P}$). The phase difference between a satellite at the ascending node and a satellite passing through the ascending node between the adjacent orbital plane constitutes F folded phases. The phasing angle, $\beta = \mathrm{F x 360°/T}$, is a parameter to determine a relative position of adjacent satellites and it ranges from 0 to P-1 [5]. The orbital inclination angle of the constellation is determined according to the latitude range of the service area [6].

Table 2. Delta pattern constellation design

T	*P*	*S*	*F*	*i* (°)	h (km)
48	8	6	2	45	888
64	8	8	1	45	888
80	10	8	1	45	888

2.3 Constellation Design and Simulation Results

We simulated walker constellation by star pattern and delta pattern. To optimize each parameter, we considered total satellite numbers and coverage time. Figure 5 shows the star pattern constellation covering on the ground-track. Figure 6 is the result of delta pattern constellation. For both cases we show MATLAB results using walkerDelta function with the option displaying sensor coverage with 10-degree elevation angle (Figs 5 and 6).

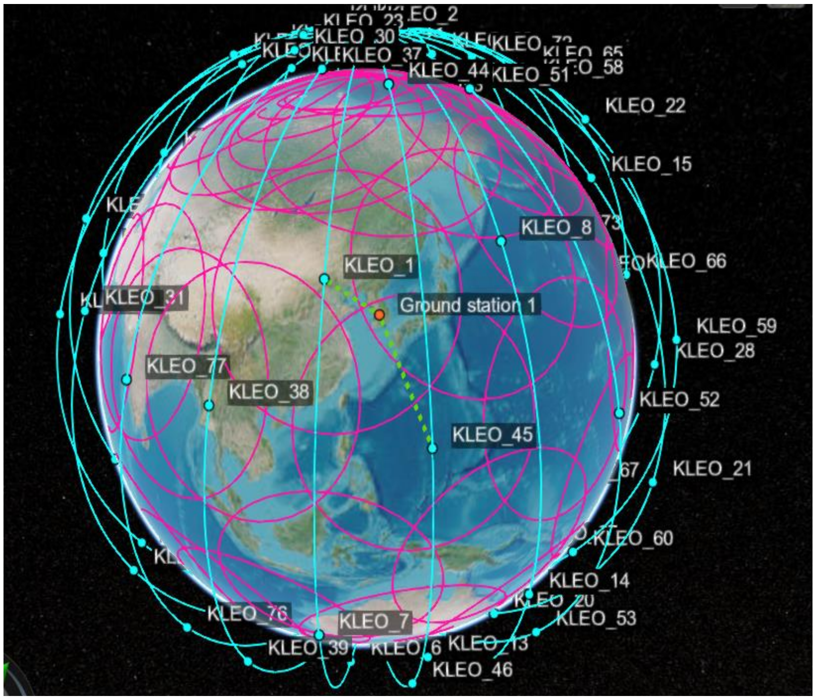

Fig. 5. Satellite constellation based on the star pattern at 888km altitude

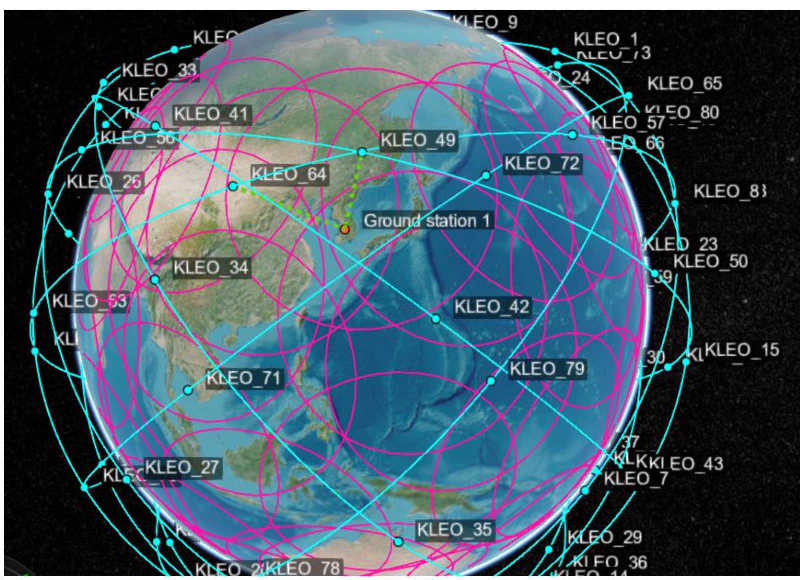

Fig. 6. Satellite constellation based on the delta pattern at 888km altitude

Also, we designed 48, 64, and 80 satellites constellation at the 888km height using delta pattern as given in Table 2. As seen in Figs. 7 and 8, the visibility of 48 satellites shows more invisibility points than 64 satellites constellation simulation. When we simulate 80 satellites using delta pattern at the height of 888km it shows fully continuous covered constellation.

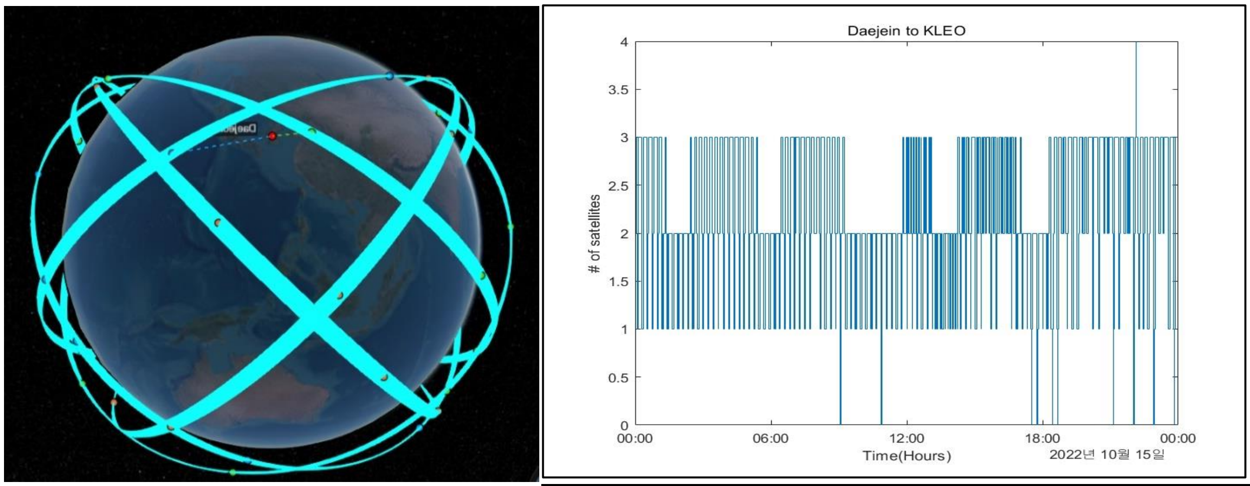

Fig. 7. Satellite constellation and visibility at Daejeon station based on the delta pattern with 48 satellites at 888km altitude

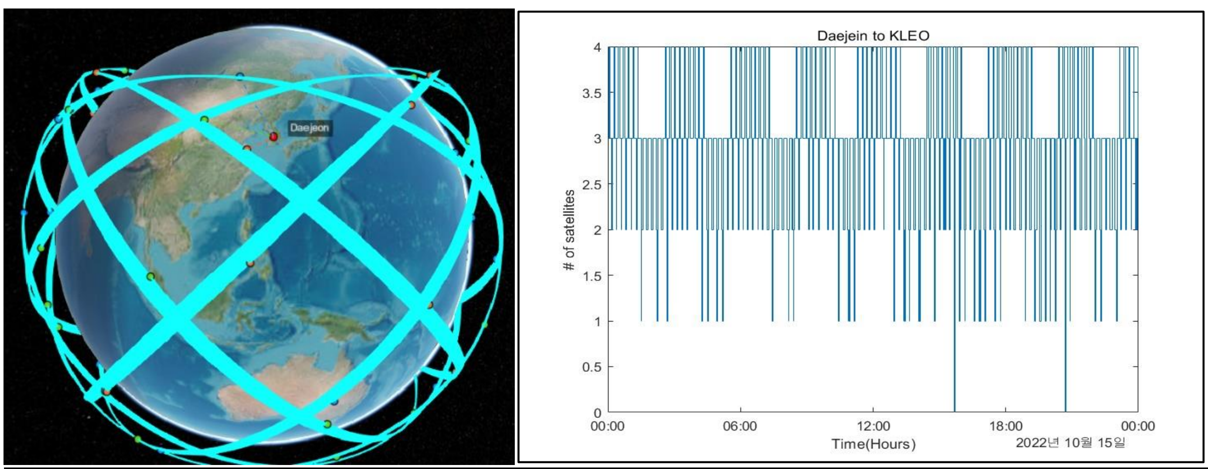

Fig. 8 Satellite constellation and visibility at Daejeon station based on the delta pattern with 64 satellites at 888km altitude

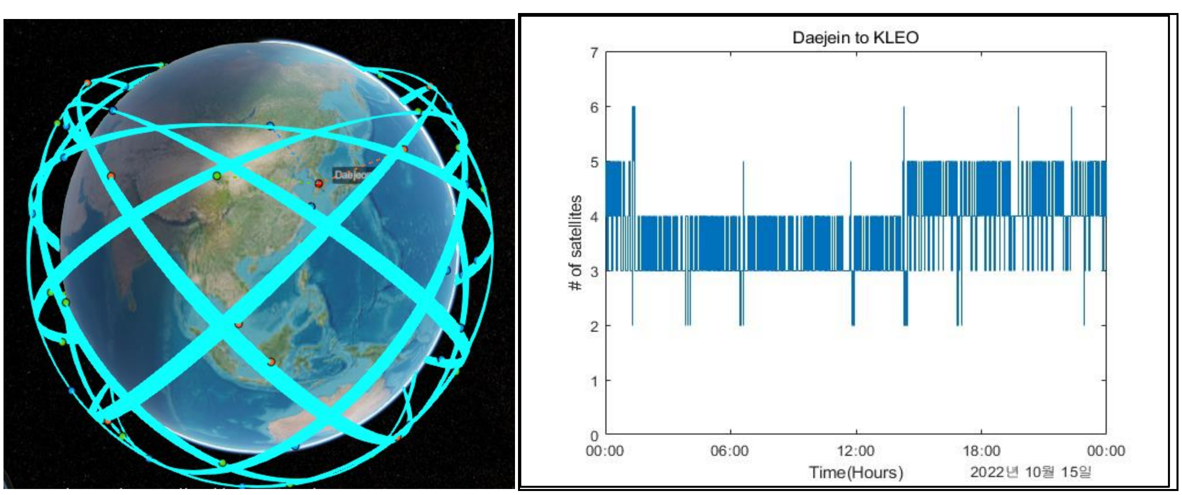

Fig. 9 Satellite constellation and visibility at Daejeon station based on the delta pattern with 80 satellites at 888km altitude

3. Conclusions

This study investigated operational scenarios that continuously cover the sky over the Korean Peninsula by star and delta patterns. First, we designed total satellite numbers using classical method to find polar orbit constellation by geometry. Second, we considered the satellite change affected by the rate of the right ascension ascending node and argument of perigee to search satellite constellation of continuous visibility. One of an important parameters of satellite constellation is the Earth-centered half-cone angle, ψ, which depends on minimum elevation angle and beam coverage angle in star pattern and the relative phasing between satellite in adjacent plane, F in delta pattern. The delta pattern can reduce total satellite numbers, but does not cover the polar area. Roughly 80 satellites can continuously cover over Korea using delta pattern (h, $T/P/i$, F ~ 888, 80/10/45, 1).

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