Conceptual Satellite Orbit Design for Korean Navigation Satellite System

Moonseok Choi,1) Dae Hee Won,2) Jongsun Ahn,2) Sangkyoung Sung,1) Jiyun Lee,3) Jeongrae Kim,4) Jae-Gyu Jang,5) and Young Jae Lee†

1) Konkuk University, Seoul 05029, Korea
2) Korea Aerospace Research Institute, Daejeon 34133, Korea
3) Korea Advanced Institute of Science and Technology, Daejeon 34141, Korea
4) Korea Aerospace University, Goyang 10540, Korea
5) Agency for Defense Development, Daejeon 34186, Korea

A regional navigation satellite system is a prospective candidate for use in the Korean navigation satellite system (KNSS), which will have South Korea and the remainder of East Asia as its service area. However, orbit design is a prerequisite for any navigation satellite system. This paper implements a conceptual design process prior to orbit design for an indigenous KNSS. Orbits are examined in terms of suitability, and an orbit combination based on the dilution-of-precision (DOP) performance is presented. Through simulation, an orbit combination capable of providing a stable DOP for the Korean Peninsula is proposed. Moreover, the orbit combination proposed incorporates design constraints such as satellite unavailability or potential position errors in the north-south direction, with the Korean Peninsula as a reference position. The simulation results suggest that the KNSS requires an orbit combination involving geostationary orbit (GEO) and elliptically inclined geosynchronous orbit (EIGSO), along with backup satellites in EIGSO; thus, the proposed system consists of 11 satellites in total.

Key Words: Satellite Orbit Design, Korean Navigation Satellite System, Dilution of Precision

1. Introduction

A satellite navigation system is a system providing navigation solutions through the use of satellites. The global positioning system (GPS) developed in the United States is the most commonly used type of satellite navigation system, and numerous countries have established GPS-based infrastructures.1,2) However, national security and sovereignty issues may arise with intensified dependency on GPS in the national infrastructure sector.1) Amid concerns about growing GPS dependency, the governments of several countries have constructed their own navigation satellite systems.1,2) These systems include the Russian global navigation satellite system (GLONASS), the European Galileo, and the Chinese BeiDou, all of which are established and operated as global service-provider systems using medium-Earth orbit (MEO) satellites.1,2) However, such global navigation satellite systems (GNSS) incur an immense initial cost, because multiple MEO satellites are required.1) In addition, large implementation and management fees are involved, and ground stations must be set up worldwide. Further, international restrictions, including International Telecommunication Union (ITU) coordination, must be met. On the other hand, compared to a global system, a regional satellite navigation system requires fewer satellites; accordingly, the implementation and management fees are lower. In addition, regional ground stations can be deployed.

© 2018 The Japan Society for Aeronautical and Space Sciences
*Received 19 February 2017; final revision received 27 September 2017; accepted for publication 12 October 2017.
†Corresponding author, younglee@konkuk.ac.kr

In response to this situation, systems such as the Japanese Quasi-Zenith Satellite System (QZSS) and the Indian Regional Navigation Satellite System (IRNSS) are being established as regional navigation satellite systems, employing 4–8 satellites.3,4) These systems will provide a regional service throughout the home nation’s own territory and also encompass neighboring regions.3,4) Note that India has recently launched the IRNSS into geostationary orbit (GEO) and inclined geosynchronous orbit (IGSO). This system is currently undergoing service testing, aiming to provide regional service throughout the Indian subcontinent through its seven satellites.4,8)

South Korea is also considering development of its own navigation satellite system as a means of preserving national security and responding to military threats, such as North Korea’s attempts at GPS signal jamming in South Korea.9) To achieve this goal, an orbit design for the Korean navigation satellite system (KNSS) must be developed prior to establishment of the system.

The requirements and constraints for the KNSS are as follows. It should be an independent navigation system with the Korean Peninsula at its center, and its service should extend throughout the East Asian region. Compared to other GNSS systems, KNSS should have lower initial costs and management costs. In addition, the system should be easy to use. Over a 24-h period, it should enable satellite placement with small dilution-of-precision (DOP) changes below the horizontal dilution-of-precision (HDOP) and the vertical dilution-of-precision (VDOP) 3, and also enables seven-satellite visibility. The conceptual design should be robust against breakdowns, maintenance and constraints for performance.
of navigation system. On the basis of these requirements, it is appropriate to have 10 regional satellites in total. The system design should have the Japanese Regional Navigation Satellite System (JRANS) concept as a benchmark, being based on Japan’s QZSS and India’s IRNSS.

Previous studies conducted in South Korea have examined the DOP, an indicator of positional measurement precision and a prerequisite parameter for navigation system design, and determined the KNSS service coverage as well as the orbit type for the satellite constellation. These studies have confirmed the efficacy of IGSO based on the DOP.\textsuperscript{10,11} Despite these efforts, however, these previous works have paid insufficient attention to the possible use of an elliptically inclined geosynchronous orbit (EIGSO), which is used in the QZSS, and have been unable to achieve continuous, stable DOP performance. Note that other countries have conducted similar studies on satellite constellation design and identified methods for DOP performance improvement. For instance, satellite constellations were uniquely designed for BeiDou, QZSS, and IRNSS, with calculation of the DOP to predict the system navigation performance.\textsuperscript{4–6} However, these previous studies examined the DOP performance for orbit constellations of navigation satellites only.

Therefore, this study investigates the orbits providing stable DOP performance to achieve an effective orbit combination design for Korea’s indigenous navigation satellite system, the KNSS. In addition, the DOP performance for each orbit combination is analyzed. The navigation performance dependence on the design parameters of the suitable orbits is examined, and an orbit combination with stable navigation performance is presented. In addition, constraints affecting the navigation performance are investigated and applied to the orbit design process. This paper proposes a new strategy to enhance navigation performance with improved stability period. This is done taking into consideration factors such as satellite unavailability and increasing in north-south position errors that may be encountered in the South Korean regions. Finally, an effective orbit combination for the KNSS is proposed.

This paper is organized as follows. Section 2 introduces the orbital elements, while Section 3 examines potential orbits for the KNSS satellite constellation and identifies those suitable for use in the final combination. Section 4 reviews various forms of the DOP and investigates the position error metrics for each examined DOP. Then, Section 5 analyzes the influence of each orbital element on navigation performance. Finally, Section 6 identifies and examines constraints on the KNSS orbit constellations, and proposes a strategy to achieve stable navigation performance. A brief concluding section is then presented.

2. Orbital Elements

In this section, the six classical orbital elements (Kepler parameters) and a parameter derived from the orbital elements are summarized. The former are listed in Table 1 and are defined as follows: The semi-major axis $a$ is the radius of an elliptical-orbit major axis; the eccentricity $e$ defines the elliptical-orbit elongation; the inclination $i$ is the angle between the orbital and equatorial planes; the argument of perigee $\omega$ is the angle between the perigee and the ascending node within the orbital plane; the right ascension of the ascending node (RAAN) $\Omega$ is the longitude from a reference direction to the ascending node of a given orbit expressed in degrees (range: $0^\circ$ to $360^\circ$); and the true anomaly $v$ is the angle between the perigee and a given satellite within the orbit plane.

| Table 1. Orbital elements and corresponding symbols/abbreviations. |
|---------------------------------------------------------------|
| **Orbital elements** | **Symbols** |
| Semi-major axis | $a$ |
| Eccentricity | $e$ |
| Inclination | $i$ |
| Argument of perigee | $\omega$ |
| Right ascension of the ascending node (RAAN) | RAAN |
| True anomaly | $v$ |

3. Orbit Suitability Analysis for KNSS

There are five orbit types that can potentially be applied in the KNSS. In this section, each of these orbit types is introduced and its suitability for the KNSS is analyzed. The most appropriate orbit combination is then determined.

A low-Earth orbit (LEO) is an orbit having a short orbital period of approximately 90 to 120 min at low altitudes of 500 to 15,000 km. Because of the low altitude and short sidereal period, the LEO orbit has smaller coverage areas and shorter serviceable hours than the alternative orbit types. Such a lower-altitude orbit incurs high costs (associated with orbit maintenance) and requires a large number of satellites if configured for a navigation satellite system; thus, LEO is unsuitable for a navigation satellite system.\textsuperscript{1,2}

An MEO, with the orbit established at an altitude of 6,000 to 20,000 km, is the most widely used orbit for GNSS.\textsuperscript{1} Compared to LEO, it facilitates larger service coverage areas. Further, through the use of up to 30 satellites, 24-h service is available.

A GEO is an orbit synchronized with the Earth’s sidereal rotation period, positioned at approximately 35,786 km above sea level and having a ground track that appears motionless.\textsuperscript{3} A high-altitude GEO facilitates secure service coverage areas and visibility; however, its considerable distance from the Earth’s surface causes high communication latency. The majority of communications satellites, including the satellite-based augmentation system (SBAS) satellites for GNSS, operate in GEO.\textsuperscript{1}
An IGSO (i.e., a 24-h synchronous orbit with zero \(e\)) is an orbit that possesses \(i\) only.\(^1\) IRNSS and BeiDou operate in IGSO. As this orbit can provide service to the northern and southern hemispheres under the same conditions, it is primarily used to cover large areas.

An EIGSO is a 24-h geosynchronous orbit having both \(i\) and \(e\). A satellite on this orbit travels between the northern and southern hemispheres, following a figure-eight-shaped ground track that becomes increasingly asymmetric depending on the magnitude of \(e\) (i.e., it becomes increasingly distorted as the ellipse \(e\) increases). This orbit is characterized by its longer period at a high elevation angle in the northern hemisphere compared to the southern hemisphere.\(^7,8\) Thus, EIGSO is used for the QZSS satellites in mid-latitude areas. This characteristic also renders EIGSO a viable candidate orbit for South Korean satellites because of the similar geographic locations of these two countries.

The above orbit suitability analysis indicates that the most appropriate orbit combination for the South Korean regions involves GEO, which can secure stable visibility, and EIGSO, which is more advantageous in the high-latitude northern hemisphere. Thus, this study develops an orbit design based on these candidate orbits, as discussed below.

### 4. DOP Navigation Performance Parameter

Navigation performance analysis can be conducted by considering the geometric conditions alone, without the need for a satellite to be physically placed into orbit. The accuracy of a system is decomposed into the user-equivalent range errors (UERE) and the geometric dilution of precision.\(^1\)

The value represented by \(\sigma_{\text{UERE}}\) is the pseudo-range error factor.\(^3\) Assuming that the system has a certain \(\sigma_{\text{UERE}}\), the DOP parameter value of the system may indicate the system accuracy. Equation (1) shows the relationship between the HDOP and the horizontal position errors, while Eq. (2) expresses the relationship between the VDOP and the vertical position error.\(^1\) As the DOP allows a user to approximate the position errors, it is used to predict navigation satellite system performance.

\[
\sqrt{\sigma_E^2 + \sigma_N^2} = \text{HDOP} \times \sigma_{\text{UERE}}, \quad (1)
\]

\[
\sigma_U = \text{VDOP} \times \sigma_{\text{UERE}}, \quad (2)
\]

\[
\sigma_E = \text{East DOP} \times \sigma_{\text{UERE}}, \quad (3)
\]

\[
\sigma_N = \text{North DOP} \times \sigma_{\text{UERE}}, \quad (4)
\]

where \(\sigma_E\), \(\sigma_N\), and \(\sigma_U\) are the \(\sigma\) values in the east, north, and vertical directions, respectively. The horizontal position-error component includes the East and North DOPs, each of which can be employed as a parameter expressing the \(\sigma\) in the east-west and north-south directions, respectively.\(^1,2\)

This study uses DOP as a threshold criterion for satellite orbit analysis. Specifically, the lower the DOP, the better the system navigation performance.

### 5. Navigation Performance Analysis Based on Orbit Design Parameters

A reference combination was selected in order to examine the navigation performance based on the orbit design parameters and analyze the DOP performance in response to design parameter variation. The IRNSS GEO and IGSO constellation was employed as the reference constellation.\(^7\) Finally, a GEO and EIGSO combination was selected for analysis, which is appropriate for mid-latitude regions. Once a synchronous orbit is selected for use, some of the orbit parameters can be assigned pre-determined values. Thus, in this study, the value of the orbital \(a\) was set to 42,164.170 km, while those of \(\nu\) and RAAN were determined from the orbital positions. Further, \(\omega\) was set to 270°, allowing satellite services to be provided at a constant altitude for long periods of time when the apogee is situated above the South Korean territory. On the other hand, the \(i\) and \(e\) of an orbit and the center longitude of the GEO placement affect the geometric conditions for a given satellite. Therefore, the navigation performance was evaluated according to these three conditions.

#### 5.1. Inclination-based analysis

With \(e\) being fixed at 0.075 and considering four equally spaced EIGSOs, satellite placement was performed to create the ground track shown in Fig. 1. For the \(e\) determination, the base \(e\) of the QZSS was adopted.\(^13\) GEO placements based on center longitudes of 80°, 127°, and 180° were considered using the IRNSS center longitude value of approximately 50° (34°E, 83°E, 131.5°E) as a reference.\(^7\) Once a reference orbit combination was created, as described above, the DOP was examined in terms of \(i\). The scope of this analysis encompassed areas exhibiting regional attributes of the Korean Peninsula, with the cities of Daejeon, Jeju, and Najin being considered as the center, southern, and northern regions, respectively. Table 2 shows the results of DOP analysis for different \(i\) values in the Daejeon area (latitude: 36.37°N; longitude: 127.36°E). In this table, the HDOP increases with higher \(i\), but decreases if \(i\) exceeds 42°. The VDOP increases continuously.

The results of the \(i\)-based DOP analysis for the Najin area...
Unlike the Daejeon area, the HDOP decreases with increasing \( i \). The VDOP has the same trend as that of the Daejeon area. Similarly, the results of DOP analysis for the Jeju area, which is located at a relatively low latitude on the Korean Peninsula, are reported in Table 4. The mean HDOP and VDOP values decrease as \( i \) increases because greater satellite visibility can be obtained with higher \( i \). No dramatic fluctuation is observed for VDOP in the Korean Peninsula, which remains at approximately 2.5. However, in the case of HDOP, an orbital \( i \) of 40–41° can be considered sufficient for the achievement of uniform (stable) navigation performance throughout the central and northern regions.

### 5.2. Eccentricity-based analysis

The orbital \( e \) is one of the Keplerian orbital elements, and a geosynchronous orbit that shares the same rotation period as the Earth serves as an orbit design parameter that determines an orbit’s ground track for a given \( e \). Recall that a GEO is a geosynchronous orbit with zero \( e \) and 0° \( i \), while IGSO is a geosynchronous orbit with non-zero \( i \).

Figure 2 depicts the ground tracks of a highly elliptical orbit (HEO), EIGSO, and IGSO with \( e \) values of 0.3, 0.1, 0.075, and 0, respectively. The orbital \( i \) is fixed at 41° and the GEO placement longitudes are 80°, 127°, and 180°. The DOP in the Daejeon area was calculated for the different \( e \) values of the three selected orbits, and the results are summarized in Fig. 3. From Fig. 3, it is apparent that the Daejeon-area HDOP initially increases with increasing \( e \), but then declines. Further, the VDOP increases with increasing \( e \) because IGSO (which has a lower \( e \) value) has more equally spaced satellites in the ceiling area of the Korean Peninsula than EIGSO. However, from Fig. 4, the IGSO satellites are visible for a short duration only (i.e., they have a short visibility time) at a high elevation angle. Overall, the average HDOP and VDOP values are low and, in order to secure continuous visibility at a high elevation angle, the use of EIGSO with an \( e \) of 0.075 is preferred rather than IGSO.

### 5.3. GEO placement-based analysis

If the newly proposed navigation satellite system operates

---

### Table 2. HDOP and VDOP with respect to satellite orbit inclination at Daejeon.

| Inclination | HDOP Mean | HDOP Max | HDOP Min | VDOP Mean | VDOP Max | VDOP Min |
|-------------|-----------|----------|----------|-----------|----------|----------|
| 38°         | 1.34      | 1.35     | 1.33     | 2.50      | 2.76     | 2.27     |
| 39°         | 1.32      | 1.33     | 1.31     | 2.49      | 2.79     | 2.24     |
| 40°         | 1.40      | 1.77     | 1.30     | 2.50      | 2.81     | 2.26     |
| 41°         | 1.43      | 1.75     | 1.28     | 2.50      | 2.84     | 2.26     |
| 42°         | 1.44      | 1.74     | 1.27     | 2.51      | 2.87     | 2.24     |

### Table 3. HDOP and VDOP with respect to satellite orbit inclination at Najin.

| Inclination | HDOP Mean | HDOP Max | HDOP Min | VDOP Mean | VDOP Max | VDOP Min |
|-------------|-----------|----------|----------|-----------|----------|----------|
| 38°         | 1.58      | 1.83     | 1.34     | 2.55      | 2.81     | 2.34     |
| 39°         | 1.58      | 1.80     | 1.33     | 2.55      | 2.84     | 2.32     |
| 40°         | 1.57      | 1.78     | 1.31     | 2.56      | 2.87     | 2.31     |
| 41°         | 1.55      | 1.76     | 1.30     | 2.56      | 2.90     | 2.30     |
| 42°         | 1.55      | 1.74     | 1.28     | 2.56      | 2.92     | 2.28     |

### Table 4. HDOP and VDOP with respect to satellite orbit inclination at Jeju.

| Inclination | HDOP Mean | HDOP Max | HDOP Min | VDOP Mean | VDOP Max | VDOP Min |
|-------------|-----------|----------|----------|-----------|----------|----------|
| 38°         | 1.34      | 1.35     | 1.33     | 2.47      | 2.73     | 2.25     |
| 39°         | 1.32      | 1.33     | 1.31     | 2.47      | 2.76     | 2.22     |
| 40°         | 1.31      | 1.32     | 1.29     | 2.47      | 2.78     | 2.20     |
| 41°         | 1.29      | 1.30     | 1.28     | 2.46      | 2.82     | 2.17     |
| 42°         | 1.28      | 1.29     | 1.26     | 2.46      | 2.82     | 2.14     |

(latitude: 42.57°N, longitude: 129.58°E) are summarized in Table 3.
based on EIGSO only, the level of satellite visibility will decline with variation in the \( i \) values, which may, in turn, have a negative effect on the DOP.\(^8\) The DOP can be expected to increase if the orbit combination includes GEO; however, the inclusion of GEO would ensure constant satellite visibility.\(^9\) This approach allows for changes in the DOP based on the GEO placement longitude, which would affect navigation performance. Thus, in this study, the EIGSO was fixed and the GEO was modified (i.e., either increasing or decreasing) in 10\(^\circ\) intervals from the reference degree values of 80\(^\circ\), 127\(^\circ\), and 180\(^\circ\) in order to examine the effects on navigation performance. The corresponding results for the mean DOP values are summarized in Table 5.

Table 5. HDOP and VDOP according to GEO placement.

| GEO placement            | HDOP Mean | VDOP Mean |
|--------------------------|-----------|-----------|
| Reference                | 1.94      | 1.87      |
| 10\(^\circ\) - interval decrease | 2.54      | 2.76      |
| 20\(^\circ\) - interval decrease | 3.32      | 4.06      |
| 10\(^\circ\) - interval increase | 1.63      | 1.39      |
| 20\(^\circ\) - interval increase | 1.46      | 1.13      |

Table 6. Elevation angle of East and West GEO according to GEO placement.

| Elevation angle of East GEO | Elevation angle of West GEO |
|----------------------------|-----------------------------|
| Reference                  | 21\(^\circ\)               | 25\(^\circ\)               |
| 10\(^\circ\) - interval decrease | 28\(^\circ\)               | 32\(^\circ\)               |
| 20\(^\circ\) - interval decrease | 35\(^\circ\)               | 38\(^\circ\)               |
| 10\(^\circ\) - interval increase | 17\(^\circ\)               | 13\(^\circ\)               |
| 20\(^\circ\) - interval increase | 5\(^\circ\)                | 9\(^\circ\)                |

and 180\(^\circ\)E were selected for use in the candidate orbit proposed.

6. Constraint-based Analysis of Navigation Performance

6.1. Navigation performance analysis based on constraints for North-South positional accuracy

The eastern and northern DOPs are the DOP parameters computed when the satellite geometry is considered while focusing on the user position (i.e., where the user position is the default location). These parameters can be regarded as criteria that express the degree of position error in the eastern and northern directions, respectively.\(^10\) In particular, the GPS satellite orbit for South Korea falls within a visible zone in the northern sky relative to the user position in which a satellite cannot be placed. Unlike GNSS, which employs a MEO orbit combination, the KNSS aims to serve as a regional navigation satellite system with a GEO and EIGSO orbit combination. Utilizing the above performance analysis based on the DOP for various orbit elements, this study proposes an orbit combination with the ground track shown in Fig. 5.\(^14\) However, this candidate orbit combination does not consider North-South positional accuracy.

In the candidate orbit combination, the total number of satellites is seven. The orbital \( i \) values for the GEO and EIGSO are 0\(^\circ\) and 41\(^\circ\), respectively. The center GEO placement longitudes are 80\(^\circ\)E, 127\(^\circ\)E, and 180\(^\circ\)E. Note that the GEO possesses the advantages of a stable DOP and constant satellite visibility at a given location. However, the fixed GEO placement that always occurs in the southern regions from the perspective of northern users may prevent the satellites from being equally spaced in the four cardinal directions. In addition, note that satellites on an EIGSO with an \( i \) of 41\(^\circ\) are observed to remain in the ceiling area of the Korean Peninsula before traveling southward, without moving northward to the northern hemisphere. Figure 5 is a skyplot of satellites in the candidate orbit proposed for the Daejeon area.

Figure 6 shows the eastern and northern DOPs for the KNSS orbit combination proposed. The mean DOP values in the eastern and northern directions are 0.84 and 1.73, respectively. This difference appears to be greater in the system proposed than in the case of GPS. Thus, the orbit combina-
tion proposed can be expected to have large position error orbit combination proposed in the north-south direction as compared to GPS.

Suggested methods to reduce the northern DOP values include increasing the satellite placement in the north by increasing the EIGSO $i$, applying a EIGSO and HEO combination, or altering the GEO placement to EIGSO or HEO. Adjusting the orbital, $i$ increases the satellite placement in the north while decreasing that in the south in accordance with the degree of change in $i$. As DOP is associated with the number of satellites, decreased satellite visibility causes DOP to increase. Therefore, eastern and northern DOPs resulting from increasing EIGSO $i$ values were determined in this study. That is, the GEO placement longitudes and the EIGSO $e$ were fixed, and DOP was examined according to changes in $i$. The results are summarized in Table 7.

North DOP declines as $i$ increases, showing a tendency to reduce the position error in the north-south direction. In contrast, an increase in VDOP is observed, which can be attributed to a failure to obtain satellite visibility.

If $e$ is increases while $i$ (i.e., GEO placement longitude and EIGSO) is fixed, eastern DOP decreases and northern DOP exhibits a tendency to increase (Table 8). This is because the increase in $e$ corresponds to satellite placement distributed in the eastern and western direction rather than to the north.

The DOP was also investigated with regard to EIGSO or HEO placement, which have center longitudes within the GEO placement longitude region. Figures 7 and 8 illustrate the ground tracks when the EIGSO, and the EIGSO and HEO center longitudes, respectively, are placed within the GEO placement longitude region in the eastern and western directions. The ground tracks are then formed in the eastern and western directions based on user position, yielding a superior satellite geometry as to fixed GEO placement. The results are summarized in Table 9. With this EIGSO and HEO center longitude placement, VDOP tends to increase while northern DOP tends to decrease.

If HEO is used, northern DOP decreases to a greater extent than in the EIGSO case (Table 9); this suggests that the HEO center longitude placement on the center longitude of the GEO, rather than EIGSO placement in the east-west direction, reduces the position error in the north-south direction more effectively.
To summarize in the context of the KNSS orbit design, the candidate orbit combination proposed, featuring GEO and EIGSO, has larger positioning error in the north-south direction than in the east-west direction. Thus, the HDOP was divided into the eastern and northern DOPs using the $\sigma$ values for the east-west and north-south position errors. Hence, the HDOP was analyzed according to variations in the orbit elements so as to determine methods for reducing northern DOP. When $i$ and $e$ were altered with regard to the EIGSO center longitude, northern DOP exhibited a tendency to decrease with increasing $i$, but decreased with decreasing $e$. When the EIGSO and HEO center longitudes were placed within the GEO placement longitude region, HEO placement caused a significant decline in northern DOP. In contrast, a relative increase in VDOP was observed. Therefore, HEO placement helps reduce northern DOP; however, other factors, such as VDOP, the total number of satellites, and satellite visibility, must also be considered when designing an orbit combination.

### 6.2. Design of orbits unsusceptible to satellite unavailability

Systems using both EIGSO and GEO require regular maintenance, such as satellite orbit maneuvers and reaction-wheel unloading.13) During maintenance, satellites become unavailable for navigation service.13) Furthermore, unexpected failure, besides planned maintenance, may cause navigation system unavailability. Accordingly, it is difficult to achieve stable navigation performance under such circumstances.

Therefore, this study examined the proposed KNSS performance with regard to satellite unavailability during initial satellite placement and for an orbit combination consisting of 7–9 satellites in total. An orbit combination that is unaffected by satellite-geometry-induced reduction in navigation performance, even if one of the satellites becomes unavailable, is also proposed. For this analysis, the orbital $i$, $e$, and center longitude of the EIGSO were set to 41°, 0.075, and 127°, respectively. The GEO placement longitudes were 80°, 127°, and 180°E. Note that, if the 80° and 180°E GEO placements are difficult to achieve, two EIGSO or HEO placements are implemented in the GEO placement longitude. The orbit elements are defined such that four EIGSOs have 90° mean anomaly intervals.

A time-lapse analysis of the DOP was conducted for a scenario in which one of the 7–9 satellites was under maintenance or out of order (Fig. 9). This shows that the orbital design does not support DOP performance where large changes do not occur for 24 h when satellites are unavailable. Based on the results, navigation performance was examined under this unavailability constraint. Two proposals were defined. Proposal 1, which is a basic proposal using seven satellites, and Proposal 2, which involves the orbit combination proposed, with two EIGSO satellites as a backup in the eastern and western GEO placement sections (Fig. 10).

The simulation results show that the satellite geometry deteriorates in a certain section under a single satellite unavailability constraint and, in turn, reduces the navigation performance. Specifically, the results show that the navigation performance is reduced when satellites are unavailable in the eastern GEO orbit, for which the reference orbit was replaced by the EIGSO (Table 10). This result indicates that there is a section in which satellite placement occurs at certain times only; this geometry causes a dramatic increase in the DOP, eventually impairing navigation performance. To design an orbit unaffected by satellite unavailability, navigation performance must be maintained by adding a satellite that traverses both the eastern and western GEO regions. This additional satellite allows an orbit to be designed such that there is no sharp decline in navigation performance.
Table 10. DOP results for Proposal 1, with unavailability in the eastern GEO.

|               | HDOP | HDOP | VDOP | VDOP |
|---------------|------|------|------|------|
|               | Mean | Max  | Mean | Max  |
| Proposal 1    | 1.91 | 2.03 | 1.84 | 2.02 |
| GEO East unavailability | 5.02 | 16.36 | 6.68 | 27.53 |

Table 11. DOP results for Proposal 2, Proposal 2 with an additional satellite, and Proposal 2 with an unavailable satellite in the eastern GEO.

|               | HDOP | HDOP | VDOP | VDOP | Total number of satellites |
|---------------|------|------|------|------|---------------------------|
|               | Mean | Max  | Mean | Max  |                           |
| Proposal 2    | 1.71 | 2.65 | 1.72 | 2.83 | 8                         |
| Proposal 2 (1 unavailable satellite) | 2.85 | 16.36 | 3.56 | 27.53 | 7                         |
| Proposal 2 + 2 satellites | 1.51 | 1.73 | 1.78 | 2.24 | 9                         |
| Proposal 2 + 2 satellites (1 unavailable satellite) | 1.71 | 2.65 | 1.93 | 2.83 | 8                         |

due to the satellite geometry in a certain section. Table 11 summarizes the mean and maximum HDOP and VDOP values obtained under the satellite unavailability constraint, when the placement combination with two EIGSO satellites in the eastern GEO of Proposal 2 was replaced by a combination featuring three EIGSO satellites (“Proposal 2 + 1 satellite”). The results show that placing three satellites in a geometrically salient eastern GEO ensures stable navigation performance, even if one of those satellites becomes unavailable. Therefore, at least three satellites must be placed in the eastern GEO or western GEO longitude to attain an orbit unaffected by satellite unavailability. The corresponding ground tracks of the candidate KNSS constellations are shown in Fig. 11.

7. Conclusion

This study aimed to develop an orbit design for the KNSS with small changes in DOP performance over the course of 24 h. Thus, the orbit suitability was examined and the DOP was analyzed in order to assess navigation performance considering various orbit elements, such as the orbital $i$, orbital $e$, and GEO placement longitude. An orbital $i$ of $40–41^\circ$, where uniform DOP performance can be expected across the Korean Peninsula, was found to be appropriate for the system. As for $e$, EIGSO exhibited superior performance to IGSO, which has zero $e$, yielding more uniform and stable HDOP and VDOP. Note that, while HEO yielded superior HDOP, VDOP performance degraded for this orbit. From this analysis, a GEO-EIGSO orbital combination was selected.

Note that the orbital elements examined in this paper were not suitable for complex analysis because DOP was calculated for varying orbital parameters, with other elements being fixed. Such orbital design elements can be constrained in order to derive appropriate parameters for the KNSS. The candidate GEO-EIGSO orbital combination involves constraints for which the north-south direction position errors appear larger than those of the east-west direction. Therefore, HDOP was divided into the eastern and northern DOPs by classifying the position error values into the east-west and north-south directions in order to identify methods of reducing northern DOP through orbit element adjustment.

A satellite unavailability simulation was also conducted to evaluate DOP when an additional satellite is placed in the existing design, for which two satellites are placed in the geometrically important eastern GEO. The results show that placing three satellites in an eastern GEO ensures stable navigation performance, even if one of the satellites becomes unavailable.

Therefore, the optimal orbit combination for the KNSS, as proposed in this paper, is an EIGSO-GEO combination with an additional three EIGSO satellites in the western GEO-eastern GEO placement longitude to provide stable navigation performance in the case of satellite unavailability. If it is decided to construct the KNSS, it is expected that the results of this study will be used as a conceptual orbit design for that system.

Acknowledgments

This work has been supported by the National GNSS Research Center Program of the Defense Acquisition Program Administration and Agency for Defense Development.

References

1) Hofmann-Wellenhof, B., Lichtenegger, H., and Collins, J.: Global Positioning System: Theory and Practice, 5th ed., Springer-Verlag, Wien, New York, 2007.
2) Kaplan, E. and Christopher, H.: Understanding GPS: Principles and Applications, Artech House Publishers, Boston, London, 2005.
3) Kawano, I., Mokuno, M., Kogure, S., and Kishimoto, M.: Japanese Experimental GPS Augmentation Using Quasi-Zenith Satellite System (QZSS), Proceedings of the 17th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS 2004), Sep. 2004, pp. 175–181.
4) Li, B., Zhang, S., Dempster, A. G., and Rizos, C.: Impact of RNSSs on Positioning in the Asia-Oceania Region, J. Glob. Position Syst., 10 (2011), pp. 114–124.
5) Ma, L. and Shengming, L.: Mathematical Aspects for RNSS Constellation with IGSO Satellites, Earth Sci. Res., 3 (2014), pp. 66–71.
6) Rao, V. G., Lachapelle, G., and Kumar, S. B.: Analysis of IRNSS over Indian Subcontinent, Proceedings of the 2011 International Technical Meeting of the Institute of Navigation (ION GNSS 2011), Jan. 2011, pp. 1150–1162.

7) Saikiran, B. and Vippula, V.: IRNSS Architecture and Applications, KIET IJCE, 1 (2013), pp. 21–27.

8) Montenbruck, O., Hauschild, A., and Steigenberger, P.: Initial Assessment of the COMPASS/Beidou-2 Regional Navigation Satellite System, GPS Solutions, 17 (2013), pp. 211–222.

9) Song, K. W.: Navigation Warfare: Threat and Response, Defense Technology, 345 (2007), pp. 38–51.

10) Shin, M. J., Lee, Y. J., Lee, G. I., and Park, C. G.: Orbit Design of a Satellite Navigation System for East Asia Region, The Society of Robot Control System, Joint Conference, 2000, pp. 158–163.

11) Lee, E. S., Lee, Y. J., Lee, G. I., Lee, J. G., Choi, H. S., and Kim, J. D.: Korean Navigation Satellite System Orbit Design, The Society of Robot Control System, National Conference, 1998, pp. 59–62.

12) Parkinson, B. W. and Spilker, J. J.: Global Positioning System: Theory and Applications, Vol. II, American Institute of Aeronautics and Astronautics, Cambridge, 1996.

13) Japan Aerospace Exploration Agency: Interface Specification for QZSS, Ver.1.8 (accessed Oct. 3, 2016).

14) Choi, M. S., Won, D. H., Sung, S. K., Lee, J. Y., Kim, J. R., Lee, Y. J., Park, J. P., and Park, H. W.: Korean Navigation Satellite System Orbit Design and Navigation Performance Analysis, The Korean Society for Aeronautical and Space Sciences, 2013 Spring Conference, 2013, pp. 645–649.