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Orbit Determination of Korea Regional Navigation Satellite System Using Inter-Satellite Links and Ground Observations

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Abstract

This study presents the orbit determination (OD) of a candidate Korea Regional Navigation Satellite System (KRNSS) using both inter-satellite links (ISLs) and ground observations. The candidate constellation of KRNSS is first introduced. The OD algorithm based on both ISL and ground observation is developed, and consists of three main components: dynamic model for Korean navigation satellites, measurement model for ISLs and ground observations, and the batch least-square filter for estimating OD parameters. As numerical simulations are performed to analyze the OD performances, the present study focuses on investigating the effects of ISL measurements on the OD accuracy of KRNSS. Simulation results show that the use of ISLs can considerably enhance the OD accuracy to one meter (design preference) under certain distributions of ground stations.

Key words: Batch Least-Square Filter (BLSF), Inter-Satellite Link (ISL), Korea Regional Navigation Satellite System (KRNSS), Orbit Determination (OD)

1. Introduction

The global navigation satellite system (GNSS), such as the Global Positioning System (GPS), has been used in a wide variety of academic/engineering/military fields for some decades. Recently, as an effort to operate their own satellite navigation system (SNS) independently and to alleviate the dependence on GPS, the regional navigation satellite system (RNSS) is being developed in some countries, such as Beidou/COMPASS (Chinese), Indian Regional Navigation Satellite System (IRNSS, India), Japanese Regional Advanced Navigation Satellites (JRANS, Japan). RNSS is an independent system for satellite navigation, and can be used for improving the navigation solution of GNSS. Korea Regional Navigation Satellite System (KRNSS) is a candidate RNSS for Korea under basic/preliminary research for providing navigational service to Korea and East Asia [1-3].

In SNS, the orbit determination (OD) of navigation satellites with high precision is critical, since it directly affects the accuracy of navigational solution. Oh et al. performed Satellite Laser Ranging (SLR) based OD of SNS to improve the OD performance [4]. While sufficient observation data from globally distributed ground stations are ideal for the OD with high accuracy, KRNSS strongly prefers to locate ground stations inside Korean peninsula for operational convenience and accessibility in emergency. This study proposes inter-satellite links (ISLs) to overcome this kind of geometric observational constraints in the OD process, and thus provide high-quality/large-amount observation data. ISL is a data communication technology between satellites, and can be applied to measure relative distance between satellites [5, 6]. Shin et al. performed real-time OD simulation of KRNSS

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using ISL measurements [7, 8] and the OD performance was shown to be improved when ISL data were added.

This study presents the OD of a candidate KRNSS with ISLs and ground observations with batch process. While the quality of OD results using batch process is better than that of using real-time OD process, batch least-square based OD is essential for providing continuous/high-quality navigational solution. ISL data is augmented to improve the quality of OD. The candidate KRNSS orbits are first introduced in Section 2. The concept of OD algorithm using ISLs and the batch least-square estimator is described in Section 3. Numerical simulation of six different cases are demonstrated to analyze the effect of ISL-augmented OD algorithm in Section 4. Finally, the conclusion follows in Section 5.

2. Korea Regional Navigation Satellite System

2.1 Candidate KRNSS Orbits

KRNSS is a candidate of Korea's RNSS. It is currently composed of three geostationary orbit (GEO) satellites, four elliptically-inclined-geosynchronous orbit (EIGSO) satellites [1-3], and ground stations inside/outside Korean peninsula. Table 1 shows the orbital elements of four EIGSO satellites. All of the EIGSO satellites are designed to have the same inclination and asymmetric 8-shaped ground tracks with 24-hour orbital period. With these configurations, they sequentially rise and fall, providing uninterrupted navigational service. In addition, there are three GEO satellites whose longitudes of ascending nodes are 80°, 127°, and 180°. Since the GEO satellites are always observable from Korean peninsula, more than four navigation satellites can be observed from Korea all the time. Consequently, these seven navigation satellites can provide independent operation of SNS, and work as a backup service for GNSS. Fig.1 describes the orbits of the candidate KRNSS. Fig. 1(a) shows four inclined EIGSO satellites and three horizontal GEO satellites in the Earth-centered Inertial (ECI) frame, and Fig. 1(b) shows the asymmetric 8-shaped ground track of the EIGSO satellites and three spots of the GEO satellites in the Earth-centered-Earth-fixed (ECEF) frame.

Meanwhile, other candidates of KRNSS are also in consideration. For example, Lee et al. [3] considers the High Elliptic Orbit (HEO) if the GEO orbits are unavailable for KRNSS, in which case additional satellites are needed to operate RNSS.

2.2 Ground Stations

Geometrically efficient placement of ground stations is essential in satellite navigation system architecture for KRNSS. Ground stations observe/monitor satellites, and transmit ephemeris data to them. Whereas stations inside Korean peninsula are preferred for operational convenience and accessibility in emergency, detailed analyses of observation sites indicate that stations outside Korean peninsula are necessary to observe/monitor those GEO and EIGSO satellites for 24 hours without discontinuity. Fig. 2 describes the elevation angles of KRNSS satellites in Daejun, Korea for 24 hours. As is seen, the elevation angles are quite low, i.e., below 20° for non-negligible period. As it is difficult

Table 1. Orbital Elements of Candidate EIGSO Orbits of KRNSS

Satellite	Semi-major Axis (km)	Eccentricity	Inclination	Argument of perigee	RAAN
EIGSO 1	42164	0.075	41°	270°	193°
EIGSO 2	42164	0.075	41°	270°	283°
EIGSO 3	42164	0.075	41°	270°	13°
EIGSO 4	42164	0.075	41°	270°	103°

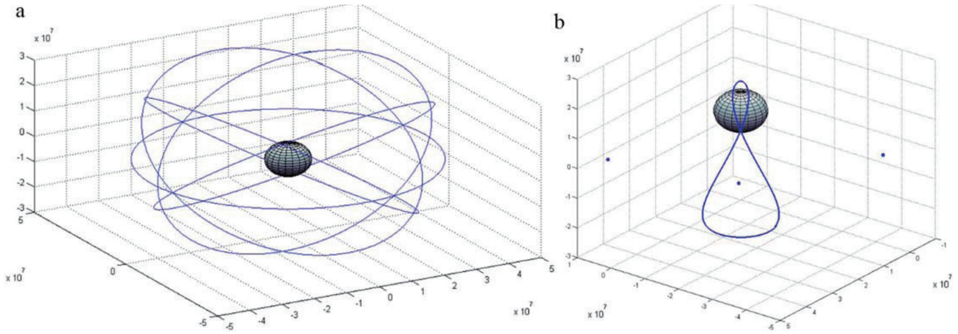

Fig. 1. (a) Candidate KRNSS Orbits in ECI Frame; (b) Candidate KRNSS Orbits in ECEF Frame

to continuously observe the EIGSO satellites for 24 hours with all stations inside Korean peninsula, additional stations outside Korean peninsula are necessary for seamless operations.

In order to analyze the effect of ground station location on OD, five domestic stations, five foreign stations [9], and one Antarctic station are considered. Table 2 shows the geometric information of these eleven ground stations. Domestic stations are distributed throughout the Korean peninsula. Foreign stations, which are currently used for QZSS of Japanese RNSS, are scattered around Asia. The Jangbogo station in Antarctica is proposed as an alternative option to mitigate geometric observational constraints. These three groups of ground stations are used to generate simulated observations for KRNSS satellites.

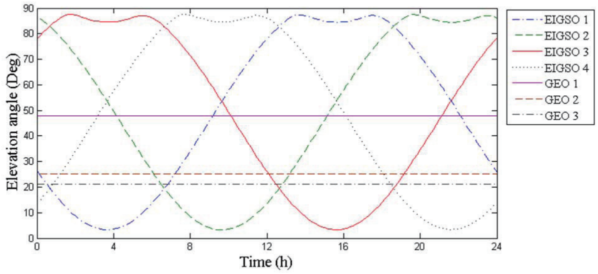

Fig. 2. Elevation Angles of Satellites Measured at Daejun

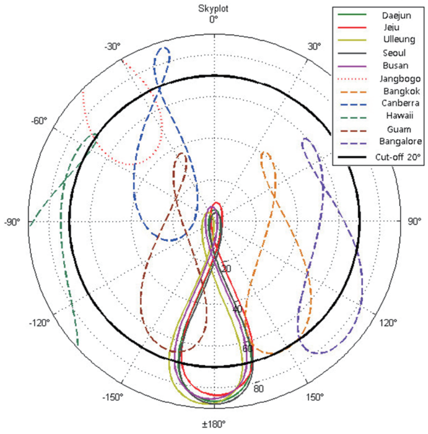

Fig. 3. Sky Plot of EIGSO Satellites Drawn from Eleven Candidate Stations

Table 2. Candidate KRNSS Ground Stations

Station	Latitude (deg)	Longitude (deg)	Station	Latitude (deg)	Longitude (deg)
Busan	35.16°N	129.05°E	Bangalore	13.03°N	77.51°E
Daejun	36.33°N	127.43°E	Bangkok	14.08°N	100.61°E
Jangbogo	74.62°S	164.20°E	Canberra	35.32°S	149.01°E
Jeju	33.40°N	126.50°E	Guam	13.48°N	144.79°E
Seoul	37.54°N	126.94°E	Hawaii	22.13°N	159.66°W
Ulleung	37.51°N	130.89°E			

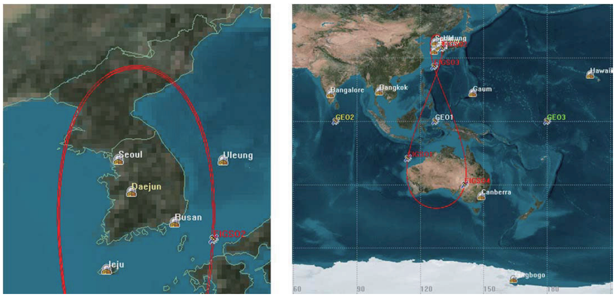

Fig. 4. Candidate Ground Stations Structure of KRNSS

Sky plot in Fig. 3 presents the observation condition for the EIGSO satellites. If the cut-off angle of observation were set to be 20°, domestic ground stations could not observe the EIGSO satellites for about 6 hours daily; foreign stations can improve observable conditions. Moreover, proper selection of foreign stations can improve the geometric structure for OD. Fig. 4 presents the whole structure of the candidate KRNSS.

3. Orbit Determination Algorithm

3.1 KRNSS Measurement Model

Due to geometric observational constraints of KRNSS, it is highly difficult to precisely determine the orbits of GEOs and EIGSOs using domestic stations only. While additional use of stations outside Korean peninsula can increase the OD accuracy, strategic combination of ground observations and inter-satellite ranging (ISR; ISL) can be also considered to effectively boost the OD accuracy. ISR [5, 6] is satellite-to-satellite ranging, corresponding to satellite-to-station in ground observations. Implementing ISR into the OD of KRNSS can improve geometric observation conditions without globally distributed ground stations. The ISR observation model is defined with signal travelling time between satellites by speed of light as

$$\begin{aligned} L &= (T_{Sat1} - T_{Sat2}) \times c \qquad (1) \\ &= (Geometric\ Distance) + c \times (\delta T_{Sat1} - \delta T_{Sat2}) + L_{error} \end{aligned}$$

where L is the ISR measurements, T is the atomic clock time in satellites, c is the speed of light, δT is the clock errors, and L_{error} is unknown measurement errors. The linearized measurement equation can be derived as

$$\begin{aligned} L - L_0 = {} & \frac{x_{Sat1} - x_{Sat2}}{L_0} \times \Delta x_{Sat1} + \frac{y_{Sat1} - y_{Sat2}}{L_0} \times \Delta y_{Sat1} \\ & + \frac{z_{Sat1} - z_{Sat2}}{L_0} \times \Delta z_{Sat1} + c \times \delta T_{Sat1} \\ & - \frac{x_{Sat1} - x_{Sat2}}{L_0} \times \Delta x_{Sat2} - \frac{y_{Sat1} - y_{Sat2}}{L_0} \times \Delta y_{Sat2} \\ & - \frac{z_{Sat1} - z_{Sat2}}{L_0} \times \Delta z_{Sat2} - c \times \delta T_{Sat2} \end{aligned} \tag{2}$$

where L_0 is calculated ISR measurements by the nominal trajectory, and (x, y, z) are the position of satellites in the ECI frame. The linearized measurement equation (2) is implemented into the batch least-square algorithm for OD, along with ground observation equations.

On the other hand, the clock and position errors of ground station are supposed to be eliminated in ground observation. That is, these errors are set to be zero by preliminary correction prior to OD. The linearized ground observation equation is similar to the equation (2) without the error term of ground station as

$$\begin{aligned} L - L_0 = {} & \frac{x_{Sat} - x_{Ground}}{L_0} \times \Delta x + \frac{y_{Sat} - y_{Ground}}{L_0} \times \Delta y \\ & + \frac{z_{Sat} - z_{Ground}}{L_0} \times \Delta z + c \times \delta T_{Sat} \end{aligned} \tag{3}$$

3.2 Dynamic Model

To calculate precise orbital position and velocity of the Earth-orbiting satellite, not only gravitational force of the Earth is considered, but also several perturbations that affect the satellite have to be taken into account. The dynamic equation of satellite is derived as

$$\ddot{\vec{r}} = -\frac{\mu_E}{r^3}\vec{r} + \vec{a}_{geo} + \vec{a}_{3rd} + \vec{a}_{\mathrm{SRP}} \tag{4}$$

where $\vec{r}$ is state vector of the satellite, μ_E is the gravitational constant of the Earth, $\vec{a}_{geo}$ is perturbation of the Earth's asymmetric gravity field, $\vec{a}_{3rd}$ is gravitational acceleration of the third-body due to the Sun and the Moon, and $\vec{a}_{\mathrm{SRP}}$ is perturbation caused by solar radiation pressure. JGM3 model is utilized for the Earth's gravitational effect. In this study, air-drag perturbation is not considered due to the high altitude of orbit of candidate KRNSS.

3.3 Batch Least-Square Filter

KRNSS OD program consists of dynamic model, measurement model, and estimation filter [10]. The measurement model includes both ISR and ground range observations. Through the dynamic model, OD algorithm calculates the nominal trajectory and generates calculated observation data. Then, the batch least-square filter iteratively finds solutions to minimize the O-C residual, i.e., the difference between observation and calculated observation:

$$z = Hx_0 + \epsilon \tag{5}$$

$$\mathrm{z} = \begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_l \end{bmatrix}, \qquad H = \begin{bmatrix} H_1\Phi(t_1, t_0) \\ H_2\Phi(t_2, t_0) \\ \vdots \\ H_l\Phi(t_l, t_0) \end{bmatrix}, \qquad \epsilon = \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \vdots \\ \epsilon_l \end{bmatrix} \tag{6}$$

Here z is the O-C residual, H is the linearized observation equations, Φ is the state transition matrix, and ϵ is the observation noise. The nominal equation (5) is used to estimate the state of the satellite at initial time.

4. Numerical Simulation

Numerical simulations are performed to quantitatively analyze the effect of the proposed ISR-augmented OD algorithm. Verification process of KRNSS OD program consists of (1) orbit propagation and observation generation and (2) orbit determination process. In the former, seven KRNSS satellites state at predetermined epoch time are used as true state vector. Artificial observation data for ISR and ground measurements are generated by adding Gaussian noise into true state vector. In addition, initial nominal states of satellites are obtained by adding artificial position errors to the true states of satellites. Then, in the latter, the batch least-square process starts from the initial nominal states of satellites, repeating estimation process until the change of RMS value of the O-C residual is lower than 1% of RMS.

Table 3 shows six different cases set up to analyze the effect of using additional ground stations outside Korean peninsula and ISR. Complete ISR observations among all satellites are assumed. Each case in Table 3 is simulated 10 times to reduce the bias by random observation noise and random nominal state error. After simulation, the estimated states are compared with true states to calculate position error. The results are provided by average value and standard

Table 3. Six Cases of OD Simulation

Case No.	Stations	Observation
1	5 Domestic	Ground
2	5 Domestic, 1 Antarctic	Ground
3	5 Domestic, 1 Antarctic, 5 Foreign	Ground
4	5 Domestic	Ground & ISR
5	5 Domestic, 1 Antarctic	Ground & ISR
6	5 Domestic, 1 Antarctic, 5 Foreign	Ground & ISR

Table 4. Simulation Parameters

Parameter	Description	Parameter	Description
Total Observation Time	8 hours	Nominal Position Error	1 km (random)
Ground Observation Noise	0.1 m (1σ, random)	ISR Observation Noise	0.45 m (1σ, random)
Ground Observation Interval	20 min	ISR Observation Interval	10 min

Table 5. Differences between Estimated and True States (Case 1, Ground Only, Average Value)

Satellite	Radial Error (m, RMS)	Along-track Error (m, RMS)	Cross-track Error (m, RMS)	3D Position Error (m, RMS)	Standard Deviation (3D Error)
EIGSO 1	0.42	6.19	4.99	8.27	4.83
EIGSO 2	0.03	2.31	1.98	3.36	2.05
EIGSO 3	0.003	1.70	1.40	2.50	1.30
EIGSO 4	0.70	2.21	4.19	5.21	2.16
GEO 1	0.82	2.69	6.75	7.82	4.85
GEO 2	0.69	4.46	3.11	6.08	4.11
GEO 3	0.65	4.34	5.18	7.18	2.85

Table 6. Differences between Estimated and True States (Case 2, Ground Only, Average Value)

Satellite	Radial Error (m, RMS)	Along-track Error (m, RMS)	Cross-track Error (m, RMS)	3D Position Error (m, RMS)	Standard Deviation (3D Error)
EIGSO 1	0.12	2.60	1.92	3.24	2.08
EIGSO 2	0.03	1.85	0.92	2.24	1.11
EIGSO 3	0.03	1.70	1.40	2.50	1.30
EIGSO 4	0.03	1.65	0.78	1.87	1.28
GEO 1	0.82	2.69	6.75	7.82	4.85
GEO 2	0.69	4.46	3.11	6.08	4.11
GEO 3	0.65	4.34	5.18	7.18	2.85

Table 7. Differences between Estimated and True States (Case 3, Ground Only, Average Value)

Satellite	Radial Error (m, RMS)	Along-track Error (m, RMS)	Cross-track Error (m, RMS)	3D Position Error (m, RMS)	Standard Deviation (3D Error)
EIGSO 1	0.02	0.12	0.07	0.15	0.08
EIGSO 2	0.02	0.07	0.18	0.22	0.13
EIGSO 3	0.02	0.08	0.32	0.34	0.25
EIGSO 4	0.02	0.10	0.11	0.16	0.08
GEO 1	0.02	0.11	0.15	0.21	0.15
GEO 2	0.04	0.33	0.48	0.67	0.34
GEO 3	0.02	0.09	0.17	0.20	0.08

Table 8. Differences between Estimated and True States (Case 4, Ground & ISR, Average Value)

Satellite	Radial Error (m, RMS)	Along-track Error (m, RMS)	Cross-track Error (m, RMS)	3D Position Error (m, RMS)	Standard Deviation (3D Error)
EIGSO 1	0.17	1.12	0.77	1.49	1.50
EIGSO 2	0.04	0.65	1.23	1.42	1.09
EIGSO 3	0.05	0.61	1.18	1.39	1.15
EIGSO 4	0.19	0.64	1.33	1.55	1.43
GEO 1	0.18	0.47	1.30	1.44	1.27
GEO 2	0.06	0.52	1.20	1.38	1.71
GEO 3	0.11	0.59	0.63	1.05	0.76

deviation. Table 4 lists simulation parameters.

Tables 5-7 present the OD results with ground observations only, and Tables 8-10 represent the OD using both ISLs and ground observations. The errors in Tables 5-10 are those of satellite states at the predetermined epoch time. Whereas Table 5 shows that the estimated satellite states are several meters offset from the true satellite states, Table 8 shows that the estimated satellite states are significantly closer to the true states of satellite thanks to ISLs. Similar results can be observed by comparing Tables 6 and 9 with each other. These results show that the proposed ISR-augmented OD algorithm improves the OD accuracy for KRNSS, compared with the OD with domestic ground stations only. While globally distributed stations can reduce the errors of estimated satellite states as shown in Table 7, those global observations in conjunction with ISLs can further improve the OD accuracy of KRNSS as shown in Table 10. Fig. 5 summarizes simulation results of KRNSS OD for Cases 1-6. The three-dimensional error shows dramatic decrease when foreign stations and ISLs are augmented into the simulation.

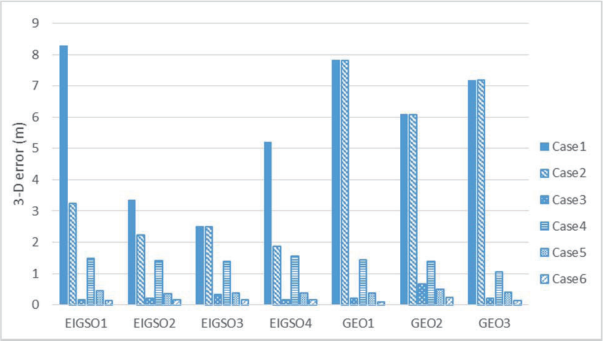

Fig. 5. 3-Dimensional Estimation Error for Case 1-6

5. Conclusions

A batch least-square filter based orbit determination strategy of a candidate KRNSS using both ISLs and ground observations was proposed. 24-hour Observation-geometry simulation was performed and the results showed that when cut-off angle was set to 20°, domestic ground stations was not independently able to observe/monitor EIGSO satellites continuously. To overcome this problem, foreign and Antarctic stations were added and continuity of EIGSO satellite observation was achieved with augmented station combination.

Simulation results successfully showed that the additional use of ISR with ground observation enhanced the OD accuracy, compared with ground observations only. Especially in the case of limited ground observations from Korean peninsula only, the ISR can be effectively used to boost the OD precision of KRNSS, which can achieve 1 m-level OD accuracy (design preference). The proposed algorithm can be also applied to orbit determination of satellites in formation flying.

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Table 9. Differences between Estimated and True States (Case 5, Ground & ISR, Average Value)

Satellite	Radial Error (m, RMS)	Along-track Error (m, RMS)	Cross-track Error (m, RMS)	3D Position Error (m, RMS)	Standard Deviation (3D Error)
EIGSO 1	0.05	0.33	0.24	0.44	0.12
EIGSO 2	0.04	0.19	0.24	0.35	0.16
EIGSO 3	0.04	0.29	0.23	0.39	0.12
EIGSO 4	0.05	0.28	0.18	0.37	0.16
GEO 1	0.03	0.29	0.17	0.37	0.14
GEO 2	0.04	0.36	0.27	0.49	0.11
GEO 3	0.06	0.33	0.17	0.41	0.15

Table 10. Differences between Estimated and True States (Case 6, Ground & ISR, Average Value)

Satellite	Radial Error (m, RMS)	Along-track Error (m, RMS)	Cross-track Error (m, RMS)	3D Position Error (m, RMS)	Standard Deviation (3D Error)
EIGSO 1	0.02	0.09	0.07	0.13	0.05
EIGSO 2	0.03	0.08	0.10	0.15	0.05
EIGSO 3	0.03	0.13	0.05	0.15	0.07
EIGSO 4	0.04	0.09	0.11	0.16	0.07
GEO 1	0.03	0.06	0.07	0.10	0.04
GEO 2	0.03	0.09	0.20	0.23	0.12
GEO 3	0.03	0.06	0.09	0.13	0.04

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References

[1] Choi, M., Won, D., Sung, S., Lee, J., Kim, J., Lee, Y. J., Park, J. P. and Park, H. W., "Korean Navigation Satellite System Orbit Design and Navigation Performance Analysis", *2013 KSAS Spring Conference*, Jeongseon, Gangwon-do, 2013.

[2] Choi, M., Ahn, J., Sung, S., Lee, J., Kim, J., Lee, Y. J., Park, J. P. and Park, H. W., "Constellation Design of Korean Navigation Satellite System Ground Station using IGNSS & ISL and Navigation Performance Analysis", *2014 KSAS Spring Conference*, Wonju, Kangwon-do, 2014.

[3] Lee, S., Park, B., Kim, D., Kim, C., Paik, B. and Lee, K., "Orbit Design of a Korean Regional Communication & Navigation Satellite System", *Journal of the Korean Society for Aeronautical & Space Sciences*, Vol. 33, No. 7, 2005, pp. 51-58. DOI:10.5139/JKSAS.2005.33.7.051

[4] Oh, H., Kim, Y. R., Park, S. Y. and Park, C., "Orbit Determination with Satellite Laser Ranging for Korea Regional Navigation Satellite System", *APISAT 2015*, Cairns, Queensland, 2015.

[5] Wolf, R., *Satellite orbit and ephemeris determination using inter satellite link*s, PhD Dissertation, Universitat der Bundeswehr Munchen, 2000.

[6] Xu, H., Wang, J. and Zhan, X., "Autonomous Broadcast Ephemeris Improvement for GNSS Using Inter-Satellite Ranging Measurements", *Advances in Space Research*, Vol. 49, No. 6, 2012, pp. 1034-1044. DOI:10.1016/J.ASR.2012.01.001

[7] Shin, K., Oh, H., Park, S. Y. and Park, C., "Real-Time Orbit Determination for Korea Regional Navigation Satellite System", *APISAT 2015*, Cairns, Queensland, 2015.

[8] Shin, K., Oh, H., Park, S. Y. and Park, C., "Real-Time Orbit Determination for Future Korea Regional Navigation Satellite System", *Journal of Astronomy and Space Sciences*, Vol. 33, No. 1, 2016, pp. 37-44. DOI:10.5140/JASS.2016.33.1.37

[9] Steigenberger, P., Hauschild, A., Montenbruck, O., Rodriguez-Solano, C. and Hugentobler, U., "Orbit and Clock Determination of QZS-1 based on the CONGO Network", *Navigation*, Vol. 60, No. 1, 2013, pp. 31-40. DOI:10.1002/NAVI.27

[10] Tapley, B. D., Schutz, B. E. and Born, G. H., *Statistical Orbit Determination*, Elsevier Academic Press, Burlington, 2004.