Satellite Autonomous Navigation with No Ground Links for Korea Regional Navigation Satellite System

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This study presents satellite autonomous navigation for Korea Regional Navigation Satellite System (KRNSS), South Korea's Regional Navigation Satellite System (RNSS) currently under conceptual design status. Assuming data link disconnection between ground segments and satellites, we present autonomous navigation algorithm and analyze its performance to maintain the desired accuracy of orbit determination (OD). Inter-satellite ranging (ISR) measurements are employed for onboard range measurement. ISR observability among KRNSS is first analyzed to validate accessibility of ISR in autonomous navigation, which is followed by real-time OD utilizing the extended Kalman filter. Simulations show that the KRNSS autonomous navigation needs more than three anchor satellites to maintain their desired OD accuracy. The average of orbital errors are 1.469 m and 0.943 m for three EIGSO/GEO anchor satellites, respectively.

Key Words: Inter-Satellite Ranging (ISR), Korea Regional Navigation Satellite System (KRNSS), Satellite Autonomous Navigation

1. Introduction

The regional navigation satellite system (RNSS) such as Indian Regional Navigation Satellite System (IRNSS, India), Quasi-Zenith Satellites System (QZSS, Japan), and Beidou/COMPASS (China) aims to cooperate with global navigation satellite system (GNSS) to enhance navigation accuracy of GNSS, and/or to offer independent navigation services when GNSS's are not available.[1)] Korea Regional Navigation Satellite System (KRNSS) is now under conceptual design status for the purpose of providing regional navigation service to East Asia. Its candidate constellation consists of four elliptically-inclined-geosynchronous-orbit (EIGSO) and three geosynchronous-orbit (GEO) satellites such that at least four navigation satellites are always visible above Korea peninsula. Figure 1 shows the ground track of the KRNSS satellites.

Since the orbit ephemeris errors of navigation satellites directly affect the navigation accuracy of ground users, it is essential to determine their orbits precisely. The previous study based on numerical simulation shows that the orbit determination (OD) with inter-satellite ranging (ISR) measurements for KRNSS satellites can be sub-meter accurate under normal conditions with ground links.[2-4)] Assuming abnormal situations of no orbit ephemeris updates from ground stations, this research presents satellite autonomous navigation to self-determine its orbit and maintain the desired ephemeris accuracy without any ground communications. For example, GPS has so far demonstrated its own autonomous navigation system (AutoNav) with GPS II-R, GPS II-F, and GPS III.[5)] In doing so, ISR technique was introduced such that AutoNav allows satellites to perform its mission for at least 180 days without ground contacts. This study follows the sequence of AutoNav to assess the autonomous navigation of KRNSS satellites.

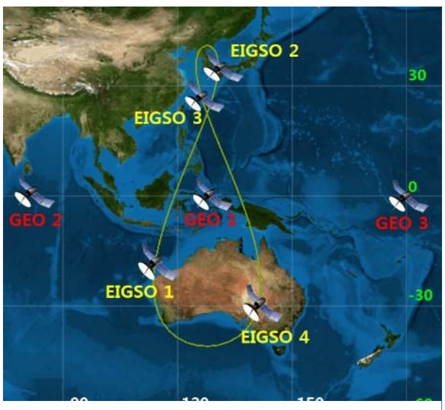

Fig. 1. Ground track of KRNSS.

This paper is organized as follows. KRNSS onboard autonomous navigation algorithm is described in Section 2 with the introduction of orbit prediction based on long-term ephemeris, ISR model, and filtering algorithm. Section 3 deals with ISR observability analysis and the associated autonomous navigation results. Section 4 draws conclusions.

2. KRNSS Onboard Autonomous Navigation Algorithm

During normal operations of KRNSS, ground segments of the navigation system periodically upload the orbit ephemeris of satellites. Then, the navigation satellites generate broadcast ephemeris through this orbit information. However, when no ground links are available for relatively long period, the orbit information cannot be renewed, and the accuracy of broadcast ephemeris becomes poorer. To maintain the precise orbit

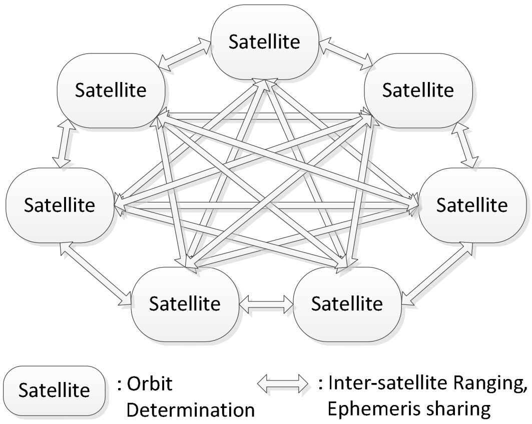

Fig. 2. Satellite autonomous navigation scheme for KRNSS.

ephemeris in this abnormal situation, satellite onboard autonomous navigation system is needed.

Figure 2 presents the schematic diagram of satellite autonomous navigation for KRNSS. Unlike normal satellite OD, satellite autonomous navigation process includes orbit ephemeris sharing part. Each satellite self-estimates its own orbit with the orbit ephemeris of other satellites and ISR measurements, and shares those results by inter-satellite crosslinks. GPS AutoNav takes this crosslink cycle for every 15 minutes by considering signal transmitting/receiving schedule.[5)]

2.1. Satellite onboard orbit prediction

In autonomous navigation, satellites' reference orbit must be predicted before the measurement update. When the orbit is predicted by numerically propagating the position and velocity from the previous orbit information, errors remaining in the previous information would be propagated as well to make the prediction become inaccurate. To reduce these errors, we adopt the method in Ref. 5) that the long-term ephemeris from the last ground upload is utilized as the reference trajectory of the orbit prediction. Figure 3 shows the onboard satellite autonomous navigation based on the long-term ephemeris.

The difference between long-term ephemeris prediction $\boldsymbol{X}_{k-1}^*$ and the given satellite orbit state vector $\widehat{\boldsymbol{X}}_{k-1}^+$ is defined as $\boldsymbol{x}_{k-1}^+$ at time t_{k-1}. Superscript + means updated state after the filtering algorithm and superscript – is the predicted state. The relation between the state differences

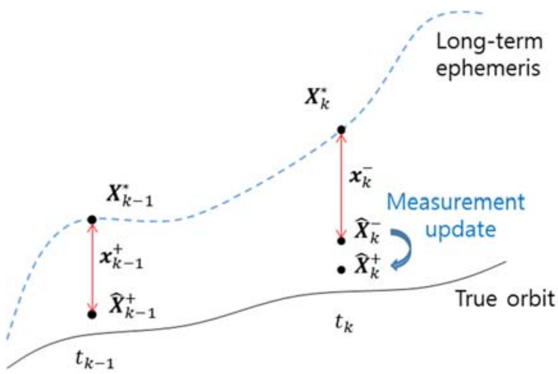

Fig. 3. Orbit Prediction based on long-term ephemeris.

$\boldsymbol{x}_{k-1}^+$ at t_{k-1} and $\boldsymbol{x}_k^-$ at t_k can be expressed as

$$\boldsymbol{x}_k^- = \boldsymbol{\Phi}(t_k, t_{k-1})\boldsymbol{x}_{k-1}^+ \tag{1}$$

where $\boldsymbol{\Phi}(t_k, t_{k-1})$ is the error State Transition Matrix (STM) from t_{k-1} to t_k. The predicted state vector $\widehat{\boldsymbol{X}}_k^-$ is obtained as

$$\widehat{\boldsymbol{X}}_k^- = \boldsymbol{X}_k^* + \boldsymbol{x}_k^-. \tag{2}$$

The predicted state $\widehat{\boldsymbol{X}}_k^-$ at t_k is updated via ISR measurements and the associated filtering algorithm in real time. In case of GPS, the accuracy of long-term ephemeris prediction is about 6 m at the end of 10 hours, 200 m at the end of 14 days, and 1500 m at the end of 180 days.[6)]

2.2. Inter-satellite ranging measurements

Due to the unavailability of ground-based satellite observation system in the abnormal situation, satellite autonomous navigation needs onboard observation. In this study, ISR is considered. The ISR measurement model simply takes the form of

$$\text{Range} = (signal\ travel\ time) \times (speed\ of\ light) \tag{3}$$

Total measurement error of ISR is assumed to include Gaussian distribution for satellite clock error, ionospheric delay, tropospheric delay, and multipath error.[7)]

2.3. Kalman filter for real-time orbit determination

The extended Kalman filter (EKF) is utilized as a real-time estimation algorithm to sequentially update the orbit ephemeris. EKF updates the state vector for every time step by a predictor-corrector concept. For the main equations and detailed filtering steps, we refer to Ref. 8).

3. Simulations of KRNSS Autonomous Navigation

KRNSS autonomous navigation simulation is divided into two parts. We first analyze the obtainability of ISR measurements for KRNSS; they cannot be obtained if an observer satellite is hidden from a target satellite by the Earth or its atmosphere. These unobservable periods are analyzed by simulation, in which the ISR measurements assume Gaussian random noise that describes potential error caused by hardware implementation, delay, etc. Then, the autonomous navigation performance with ISR measurements is assessed by following the sequence of GPS AutoNav.

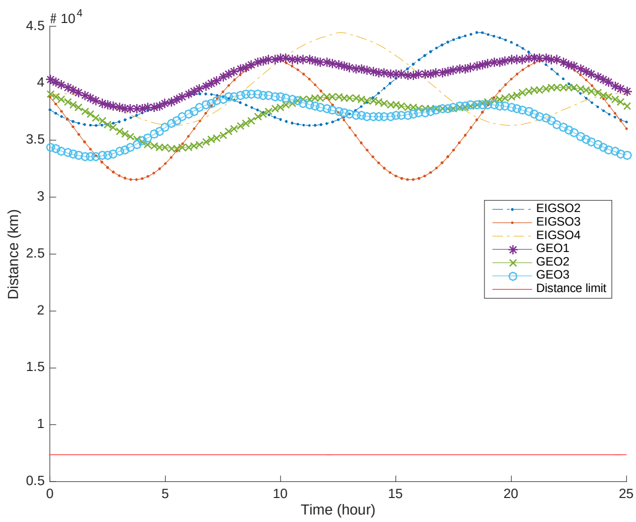

Fig. 4. ISR visibility analysis of EIGSO1.

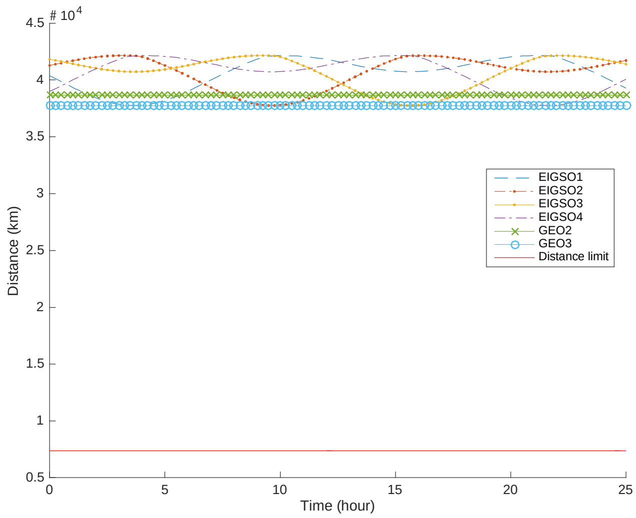

Fig. 5. ISR visibility analysis of GEO1.

3.1. ISR observability simulation

In this simulation, the sheltering area limit is set as the Earth's radius (6,378.137 km) plus 1,000 km to account for the Earth and its atmosphere/ionosphere.

Figures 4 and 5 show the visibility simulation results. Among three GEO and four EIGSO satellites, one of each kind is presented because the observability depends on the orbit type. The distance on the *y*-axis is the shortest (perpendicular) distance between the travel path of ISR signal and the center of the Earth. If this value is smaller than the Earth radius plus 1,000 km, then ISR data would be blocked and unobtainable. The results show that ISRs among KRNSS satellites are not blocked at all by the Earth and its atmosphere thanks to high altitudes of KRNSS satellites.

3.2. Autonomous navigation simulation

KRNSS's autonomous navigation simulation is spanned for one week. ISR measurements are numerically generated with Gaussian random noise of one sigma standard deviation of 0.45 m.[9] ISR data generation, orbit prediction, and state estimation are obtained every 15 minutes, following the case of GPS AutoNav. [5]

As the most problematic situation, autonomous navigation with all seven satellites of KRNSS at once faces several problems. The first one is that the absolute position cannot be estimated as the ISR only measures the relative distance between two satellites. Therefore, ISR measurements cannot detect translational and rotational motion of the satellite constellation. Figure 6 depicts this problem. The red triangle,

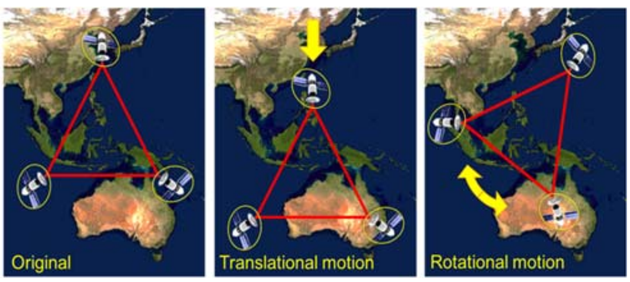

Fig. 6. Problem of ISR on KRNSS autonomous navigation.

which represents the relative range among three satellites, does not change even there are translational/rotational motions of the satellites. Therefore, to eliminate this issue, several anchor satellites whose exact orbits are known should be considered. In this research, six different cases are tested by changing the number/configuration of anchor satellites and target satellites as shown in Table 1. Cases 1-2, 3-4, and 5-6 refer to one, two, three anchor satellites, respectively.

Table 1. KRNSS autonomous navigation simulation cases.

Case	Anchor satellite(s)	Target satellites
1	1 EIGSO	3 EIGSO, 3 GEO
2	1 GEO	4 EIGSO, 2 GEO
3	2 EIGSO	2 EIGSO, 3 GEO
4	2 GEO	4 EIGSO, 1 GEO
5	3 EIGSO	1 EIGSO, 3 GEO
6	3 GEO	4 EIGSO

Figures 7 and 8 present KRNSS autonomous navigation for cases 1-2 and 3-4, respectively, all of which show that three-dimensional position errors diverge over time with *two anchor* satellites. Although the diverging rate is slower than that for the case of one anchor satellite, the position errors of cases 1-4 grow gradually. These results indicate that one or

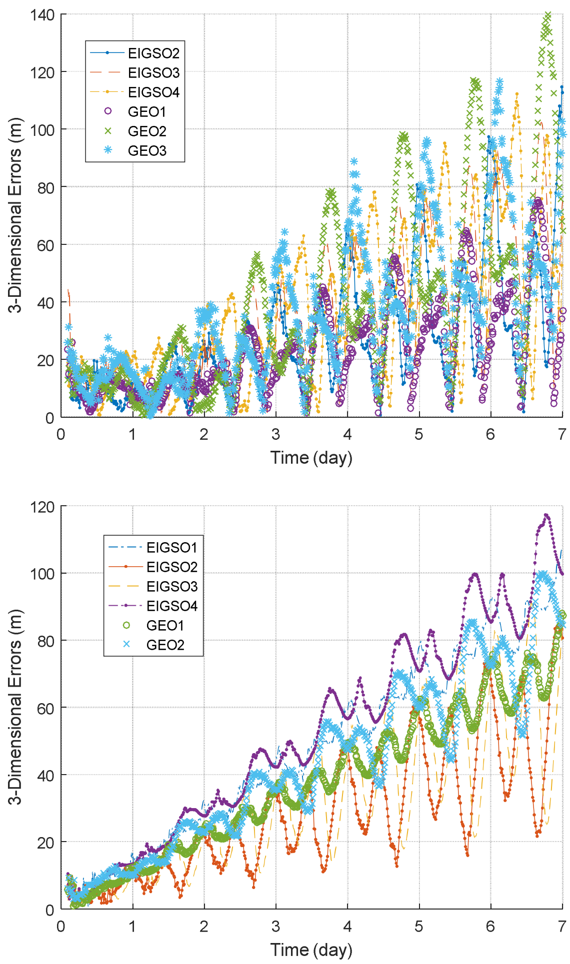

Fig. 7. KRNSS autonomous navigation results using two anchor satellites (top: 1 EIGSO, bottom: 1 GEO).

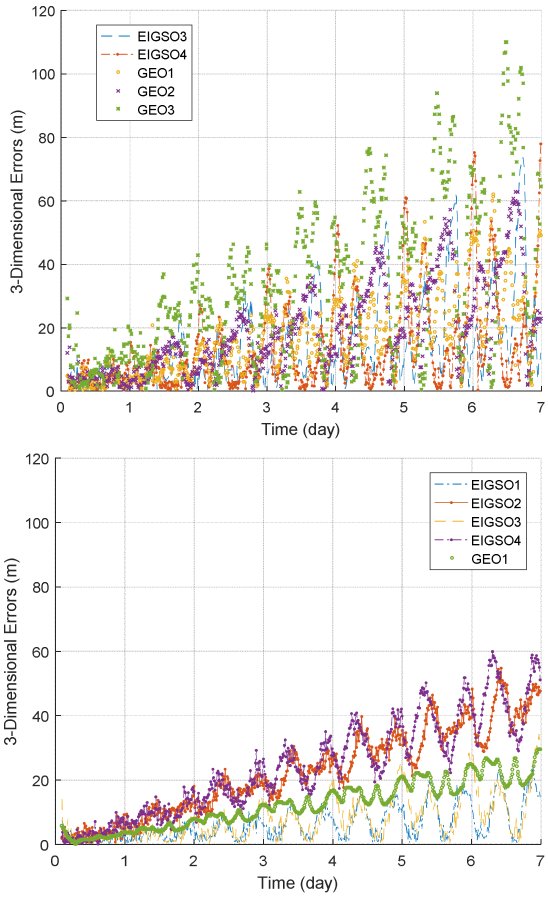

Fig. 8. KRNSS autonomous navigation results using one anchor satellite (top: 2 EIGSO, bottom: 2 GEO).

two anchor satellites cannot achieve the orbital accuracy high enough to carry out the independent navigation mission, unless additional observation or help is available.

On the other hand, Figs. 9 and 10 show that autonomous navigation accuracy remains precise for the whole simulation period with three anchor satellites. The average of three-dimensional orbital errors of four target satellites are 1.469 m and 0.943 m for Cases 5 and 6, respectively to satisfy

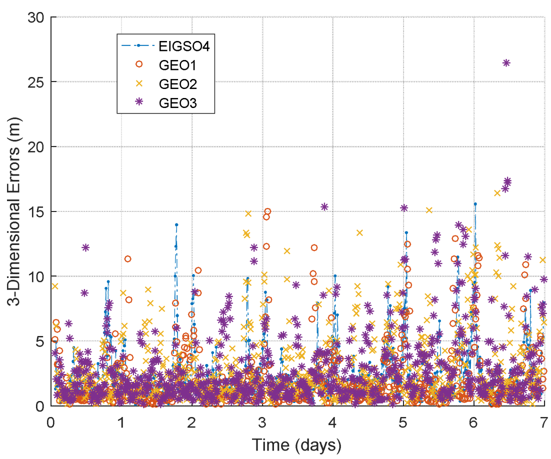

Fig. 9. KRNSS autonomous navigation results with three EIGSO anchor satellites.

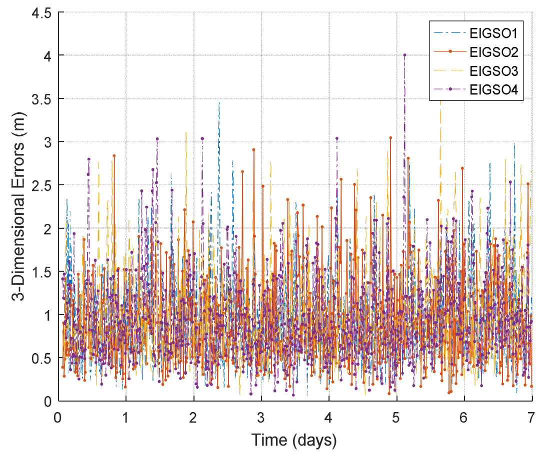

Fig. 10. KRNSS autonomous navigation results with three GEO anchor satellites.

the requirement of GPS AutoNav.[5)] Also, when there exist more than three anchor satellites, the autonomous navigation successfully performed to maintain the desired OD accuracy for the whole simulation time.

4. Conclusion

The autonomous navigation simulation of KRNSS satellites was presented with no ground links. The ISR measurement was considered as onboard observation, and it was available for all time due to high altitudes of KRNSS satellites compared with the Earth radius. Analyses by numerical simulations showed that more than three anchor satellites were required for autonomous navigation of KRNSS satellites, and that the more anchor satellites, the higher OD accuracy of the autonomous navigation. The precise OD of anchor satellites is essential to extend the lifetime of navigation mission.

To secure more than three anchor satellites in the abnormal situation, there must be a way to estimate the anchor satellites' orbit without utilizing ground-based observation. We now consider two candidate measurements to address this issue: ISR from other existing GNSS/RNSS and celestial measurements based on star-tracking. These are left as future work.

Acknowledgments

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

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