Technical Paper
J. Astron. Space Sci. 37(2), 105-115 (2020)
https://doi.org/10.5140/JASS.2020.37.2.105

JASS Journal of Astronomy and Space Sciences

Space Surveillance Radar Observation Analysis: One-Year Tracking and Orbit Determination Results of KITSAT-1, "우리별 1호"

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The Korean Institute of Technology Satellite (KITSAT-1) is the first satellite developed by the Satellite Technology Research Center and the University of Surrey. KITSAT-1 is orbiting the Earth's orbit as space debris with a 1,320 km altitude after the planned mission. Due to its relatively small size and altitude, tracking the KITSAT-1 was a difficult task. In this research, we analyzed the tracking results of KITSAT-1 for one year using the Midland Space Radar (MSR) in Texas and the Poker Flat Incoherent Scatter Radar (PFISR) in Alaska operated by LeoLabs, Inc. The tracking results were analyzed on a weekly basis for MSR and PFISR. The observation was conducted by using both stations at an average frequency of 10 times per week. The overall corrected range measurements for MSR and PFISR by LeoLabs were under 50 m and 25 m, respectively. The ionospheric delay, the dominant error source, was confirmed with the International Reference of Ionosphere-16 model and Global Navigation Satellite System data. The weekly basis orbit determination results were compared with two-line element data. The comparison results were used to confirm the orbital consistency of the estimated orbits.

Keywords: KITSAT-1, radar, tracking, orbit determination

1. INTRODUCTION

The Korean Institute of Technology Satellite (KITSAT-1) is the first Korean artificial satellite on low Earth orbit (LEO). KITSAT-1 was developed by the Satellite Technology Research Center (SaTReC) and the University of Surrey and was launched from Guiana Space Centre on August 10, 1992. The nickname of KITSAT-1 is "우리별 (Our star)." The Satellite Catalog Number is 22077 and the international ID is 1992-052B. The main mission of KITSAT-1 was satellite technology training and education for satellite engineering. The expected lifetime was five years, but actual communication had been maintained for 12 years.

KITSAT-1 is a small-sized satellite on LEO. The launch mass is 48.6 kg and the physical size is 35.2 cm × 35.6 cm × 67 cm. The orbit of KITSAT-1 was designed for a 1,320 km circular orbit with 66 degrees of the orbital inclination. The semi-major axis has been decreased by only 2 km since it launched. The mean motion is maintained at about 111 minutes per revolution.

After KITSAT-1, 11 Korean satellites have been launched on LEO. The Korea Multi-Purpose Satellite series satellites had been developed by the Korea Aerospace Research Institute for observing the Earth, while the KITSAT series, Science and Technology Satellite series, and NEXTSat-1 satellites were developed for acquiring technical training and performing science missions. Among 12 LEOs, KITSAT-1 has the highest altitude and the smallest physical size. Therefore, both the ground-based optical and the radar tracking of KITSAT-1 are regarded as the most challenging for the observation of Korean LEOs.

Space Situational Awareness (SSA) activity aims to get orbital and physical information for space objects. SSA activity in Korea was initiated by supporting the re-entry response team for COSMOS 1402. The research activity of Korean SSA by the Center for SSA of the Korea Astronomy

Received 25 FEB 2020 **Revised** 8 APR 2020 **Accepted** 9 APR 2020
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and Space Science Institute (KASI) has been focused on the development of the optical, laser, and radar facilities, the orbit determination (OD), and the study of the characteristics of space objects up to the present (Jo et al. 2011; Park et al. 2018). Optical Wide-field patrol Network (OWL-Net) had been developed as the first dedicated SSA facility in Korea from 2010 to 2016. Followed by the objectives of the OWL-Net, the OD technique and strategy research have also been performed with the real observation data (Choi et al. 2015; Lee et al. 2017; Choi et al. 2018; Choi et al. 2019). The radar system study had been carried out as one of the next phases of SSA activity in Korea (Choi et al. 2018; Lee et al. 2018; Moon et al. 2018).

The radar system is used for tracking space orbiting objects to support the analysis of space hazards such as collision and re-entry. LeoLabs, a space radar development and operation company, presented commercial space tracking services with space objects tracking and OD performance (Griffith et al. 2017; Griffith et al. 2019). They have provided the radar measurements and the estimated orbit information for thousands of LEOs for satellite operators and researchers (Nicolls et al. 2017; Archuleta & Nicolls 2018). The quality of the space surveillance radar measurements are affected by refraction, troposphere and the ionosphere (Montenbruck 2005; Vallado 2013). The errors occur in the measurements of the azimuth, elevation, and the range (Hapgood 2010). Griffith et al. (2018, 2019) presented that the range measurements of LeoLabs radars typically represents a difference near 15 meters from the truth. In a simulation study using a ray tracer for UHF (435 MHz), the range errors have predominantly been shown in the 0 to 150-meter range (Jones 2017). The range of the observation errors of LeoLabs was similar with the simulation study for UHF space surveillance radar in the study of Jones et al. (2017). However, previous reports from LeoLabs presented the bias and the residuals of measurements for specific LEO satellites of interest for several days. In addition, the long-term variation of the observation bias due to the ionosphere and the system has not been separately analyzed. In the first dealing with the actual radar observation, we attempted to analyze the quality of the space surveillance radar observation measurements by part of part for long-term steady maintenance of the estimated orbits of KITSAT-1.

In this study, we analyzed the radar tracking results and performed the OD test using the radar measurement made by LeoLabs for KITSAT-1. The radar tracking results for KITSAT-1 in 2018 were produced with two stations in the U.S., the Midland Space Radar (MSR) in Texas and the Poker Flat Incoherent Scatter Radar (PFISR) in Alaska. The number of arcs per week, detected range variation, and the corrected range error (uncertainty) variation were investigated for each site. The OD test was performed for single- and double-station. First, the weekly basis OD results with both stations were compared with publicly accessible orbital information, that is, the two-line elements (TLEs). We also performed the orbit estimation test with the single-station data from MSR. This test can provide the basis for estimating the performance of a single radar for KITSAT-1.

2. KITSAT-1 TRACKING RESULTS IN 2018

2.1 LeoLabs Radar Facilities

The MSR and PFISR facilities are using UHF (440 and 450 MHz for MSR and PFISR, respectively) and the elevation limit is 30 degrees. MSR is a one-dimensional radar with a fan-shaped beam, while PFISR is a two-dimensional radar. MSR and PFISR radars can track a total of 1.5 million objects per month for 6,000 LEOs and 5 million objects per month for 9,000 LEOs, respectively. A third radar station, Kiwi Space Radar (KSR), of LeoLabs was established in New Zealand in October 2019 (LeoLabs n.d.). Originally, PFISR was one of the Incoherent scatter radars to probe the upper atmosphere (Nicolls 2015). LeoLabs radars are non-rotating phased array radar. Table 1 shows LeoLabs radar's location. LeoLabs radars averagely made the observation for prioritized targets of one or two times per day (Nicolls & McKnight 2019).

2.2 The Observation Model of Space Surveillance Radar

Space surveillance radars have commonly used the two-way ranging method with a transmitter and receiver for unspecified space objects. The range measurements with the delay errors for space surveillance radars can be described as

$$R = R_{sr} + R_t + R_i + w_r \tag{1}$$

where R_{sr} is a two-way range, the tropospheric delay R_t and the ionospheric delay R_i are also considered the two-way method. w_r is white Gaussian thermal noise including the transmitter thermal noise, clock errors, and signal delay errors by the designed radar system.

Table 1. LeoLabs radar's location

Radar	Location	Latitude (degree)	Longitude (degree)
PFISR	Fairbanks, Alaska, USA	65.13 N	147.47 W
MSR	Midland, Texas, USA	31.96 N	103.23 W

PFISR, Poker Flat Incoherent Scatter Radar; MSR, Midland Space Radar.

As mentioned above, the measurements of MSR and PFISR using UHF are affected by the atmospheric refraction. The tropospheric delay dominantly varies with the elevation angle while the ionospheric delay is more sensitive depending on wave frequency. The LeoLabs has provided the raw and corrected measurements including the uncertainty and the correction for the ionospheric delay and the system bias.

2.3 The Quantitative Analysis of Tracking Results

The LeoLabs radar has made the observation of KITSAT-1 for 1,375 arcs with 62,449 measurements using two stations through October 20, 2019. The number of monthly observations was about 40 arcs with about 1,500 measurements. Fig. 1. shows the number of arcs and observation points that were measured on a weekly basis for KITSAT-1 in 2018. The total number of the observed arcs using PFISR was 349, while the number of the observed arcs was only 157 using MSR. In the case of the observation point, PFISR made 20,250 observation points in 2018 which was about seven times more than that of the 2,913 observation points made using MSR. The differences of the observed arcs and the observation points were caused by the latitudinal position of each station and the observation field-of-view (FoV) shape. The lowest elevation angle of the observation for KITSAT-1 of the two stations was 60 degrees.

In the 12th week of 2018, there was no observation for both stations. Further, TLEs were also not updated for several days during this period. However, observations of other space objects were normally performed. In general, LeoLabs provided the raw, the bias corrected and fit-ready measurements with uncertainty and correction values (system bias and ionospheric delay) for all observations. They also provided both raw and corrected radar cross-sectional (RCS) values.

2.4 The Measurements Error Analysis

The range errors for KITSAT-1 in 2018 provided by LeoLabs were analyzed. LeoLabs provided bias-corrected and fit-ready range measurements with uncertainties as the measurement data. The range error referred to range uncertainty for the corrected range by the effects of space weather and system errors. Fig. 2 shows the range errors daily distribution and histogram for MSR and PFISR for KITSAT-1 in 2018. The range error of MSR is larger in range than that of PFISR. The range errors in the daytime of PFISR are bigger than them in the nighttime, while the range errors of MSR are uncorrelated with daily time. The range of variation in range errors of PFISR was about 5 m (13–18 m) for KITSAT-1 in 2018, while the range of variation in range errors of MSR was about 20 m (8–28 m). The range error varied on a daily basis. The range of the range errors for KITSAT-1 of both stations is similar to that of previous studies for other satellites (Griffith et al. 2017). The range measurement from radars in lower latitudinal positions can be more impacted by the ionosphere.

The differences between the corrected range and the raw range of both stations for KITSAT-1 in 2018 were analyzed. Griffith et al. (2017) described that the range measurements averagely had daily bias corrected-residuals under 15 m with high-accuracy ephemerides as computed by the International Laser Ranging Service (ILRS). The corrected values included the correction for the space weather effects and the system error. The range correction (corrected range – raw range) was sum of the range bias and the ionospheric delay. The system bias was checked once per day with the truth. Therefore, the daily variation for the correction was caused by the ionospheric delay. The range of variation in the range correction for MSR was 50 m, while the range of

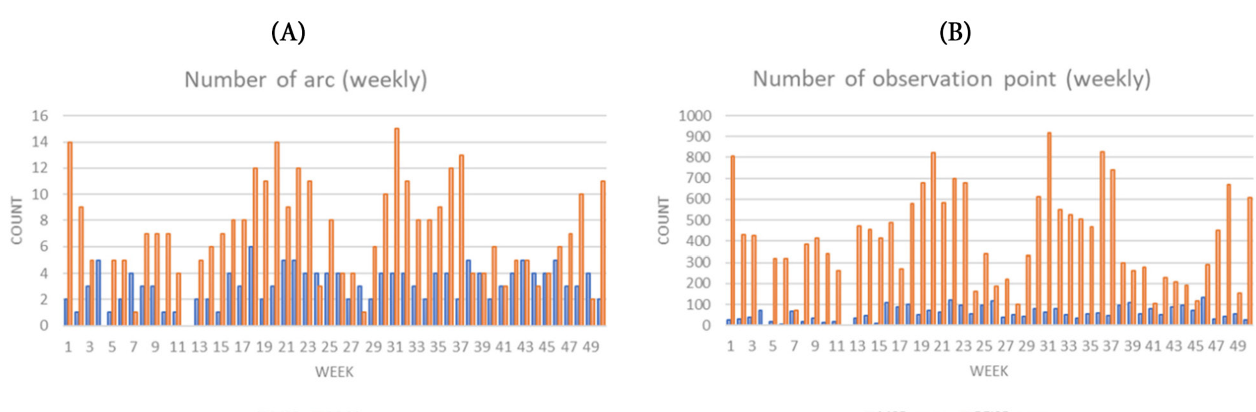

Fig. 1. Distribution of the number of arcs (A) and observation points (B) measured on a weekly basis for KITSAT-1 using MSR and PFISR in 2018. KITSAT, Korean Institute of Technology Satellite; MSR, Midland Space Radar. PFISR, Poker Flat Incoherent Scatter Radar.

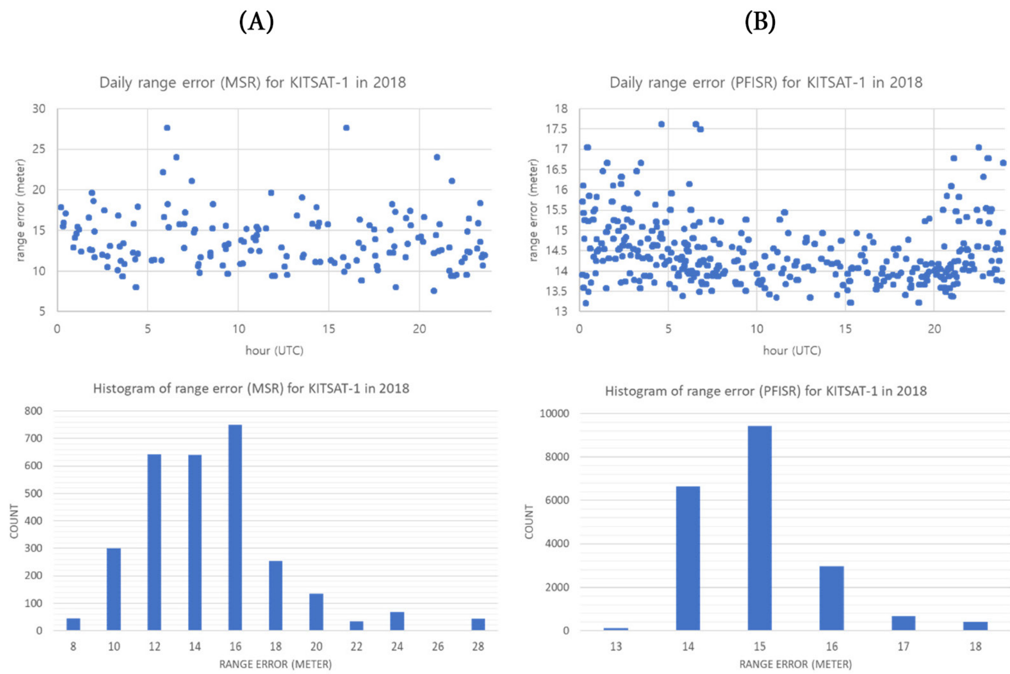

Fig. 2. Range error (range uncertainty) daily distribution and histogram for MSR (A) and PFISR (B) for KITSAT-1 in 2018. MSR, Midland Space Radar; PFISR, Poker Flat Incoherent Scatter Radar; KITSAT, Korean Institute of Technology Satellite.

variation in the range correction for PFISR was 25 m in Fig. 3. As mentioned above, the error due to the tropospheric delay is under a few meters, and the ionospheric error is more dominant for the correction of the radar data. We described the ionospheric correction in the next section below.

The calculated maximum physical cross-section area of KITSAT-1 does not exceed one square meter. Although the radar cross-section (RCS) is not exactly fitted with the actual physical size, we investigated the RCS of KITSAT-1 from the measurements of LeoLabs. Fig. 4 shows the distribution of the RCS of registered space objects in the Satellite Catalog (SATCAT) and the RCS for KITSAT-1 (red circle) on the left

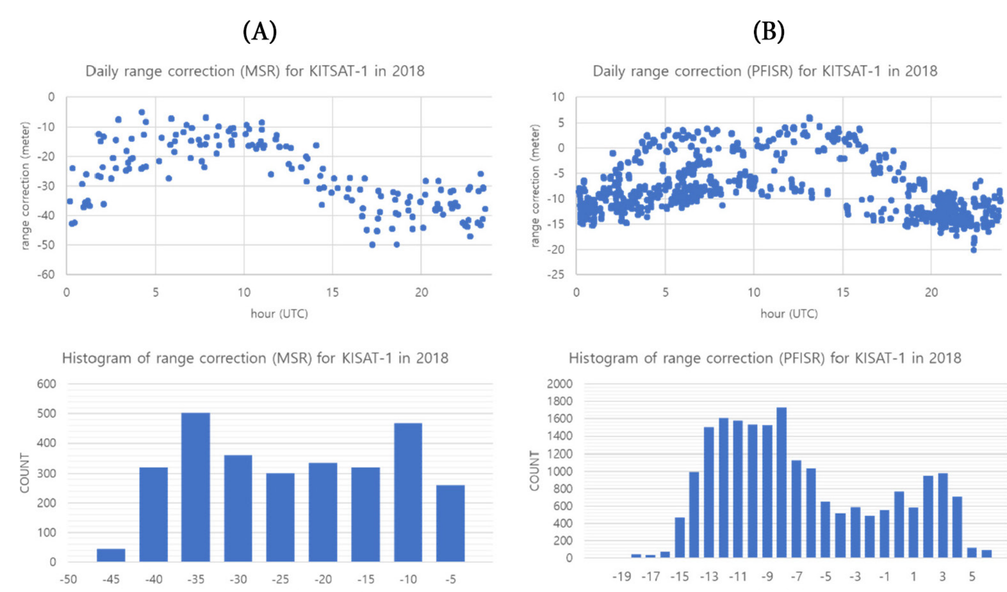

Fig. 3. The range correction daily distribution and histogram for MSR (A) and PFISR (B) for KITSAT-1 in 2018. MSR, Midland Space Radar; PFISR, Poker Flat Incoherent Scatter Radar; KITSAT, Korean Institute of Technology Satellite.

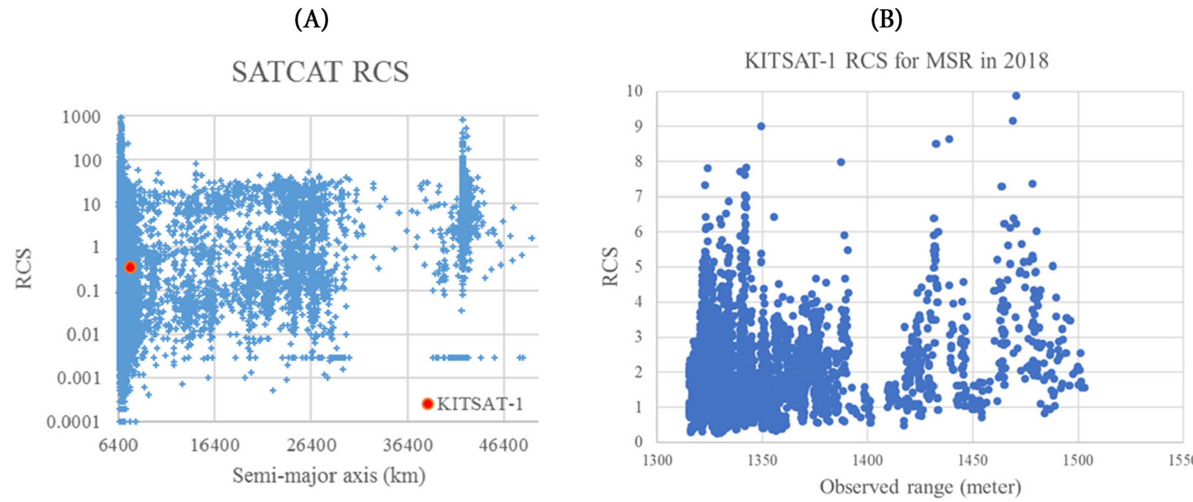

Fig. 4. Distribution of the RCS of space objects and KITSAT-1 RCS (A) from the SATCAT and the observed RCS of KITSAT-1 (B) by the MSR radar of LeoLabs in 2018. RCS, radar cross-section; KITSAT, Korean Institute of Technology Satellite; SATCAT, satellite catalog; MSR, Midland Space Radar.

side. On the right side, the distribution of the corrected RCS versus the observed range in the MSR of KITSAT-1 was shown. The corrected RCS values were calculated and provided by LeoLabs. We expected that the RCS of KITSAT-1 would decrease as the range measurement increased. However, the variation of the RCS was too large to identify a correlation between the RCS and the range variation. The RCS values from LeoLabs were bigger than the maximum physical cross-section area of KITSAT-1. The observed RCS for KITSAT-1 of PFISR showed similar trends. The calculation process of the RCS in LeoLabs data was not described in detail.

2.5 The Ionospheric Delay Error Analysis

The minimum observation elevation for MSR and PFISR for KITSAT-1 was 60 degrees in 2018. The tropospheric delay was under 10 m with the observed elevation angle (Moon et al. 2018). Mapping functions such as the models developed by Marini-Murray and Mendes-Pavlis and the zenith component function such as the Crane model have been used to correct the errors for space surveillance radars. On the other hand, the ionospheric delay can increase up to hundreds of meters for UHF radars (Jones et al. 2017; Moon et al. 2018). The ionospheric delays have usually been corrected with models such as those of Klobuchar, NeQuick, and the International Reference Ionosphere (IRI) or by plural frequency sensing such as Global Positioning System (GPS). GPS and Global Navigation Satellite System (GNSS) systems have provided the Total Electron Content (TEC) value for calculating the slant TEC for certain observed space objects with higher accuracy than other models (Han 2004; Asmare et al. 2014). However, the ionosphere models have the advantage of being able to provide the ionospheric delay in real time and in the near future.

The IRI-2016 model was used to calculate the ionospheric delay of MSR and PFISR. Fig. 5 shows the daily variation of the ionospheric delay of MSR and PFISR for KITSAT-1 observation in 2018. The ionospheric delay of MSR only shows unitary daily variation, while the daily variation of PFISR shows two different variations. In the daytime, the ionospheric delay of both stations is higher than in the nighttime (about 5–15 hours in UTC). And the ionospheric delays of PFISR during the winter season are smaller than those of the summer season. However, the difference in the amount of the ionospheric delay in the daytime is larger than at nighttime. Further investigation was attempted for the observational characteristics to analyze the daily ionosphere delay difference between the two stations.

We investigated the annual variation of the ionospheric delay (correction). The ionospheric delay of MSR was not correlated with seasonal variation. In the case of PFISR, the annual variation of the ionospheric delay showed variation, but was not consistent with the four seasons. Fig. 6 shows the annual variation of the daily observation time for KITSAT-1 in UTC and the annual variation of the ionospheric delay for KITSAT-1 of MSR and PFISR. The observation time varies periodically for both stations. In the case of MSR, the observation is performed in both the daytime and nighttime and the correlation was unclear. However, the ionospheric delay for KITSAT-1 of PFISR shows a clear correlation with the observation time. Only the ionospheric delays at nighttime vary with the seasons. This means that the observation time during the day is more dominant for the ionospheric

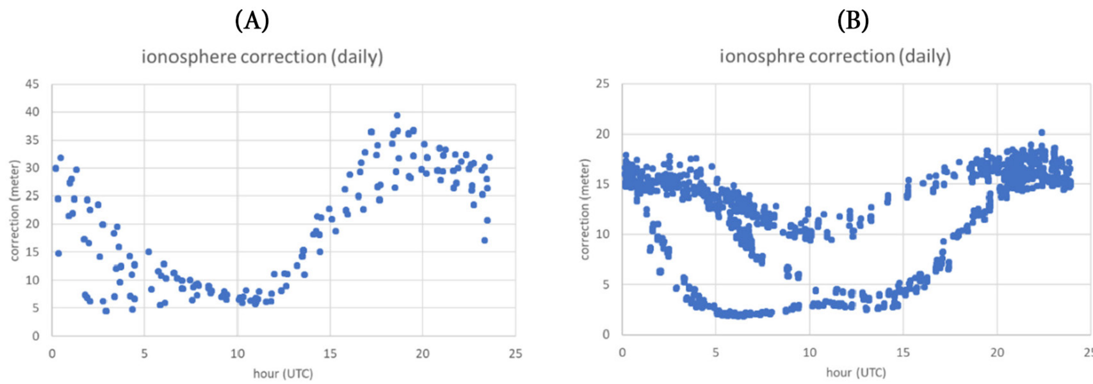

Fig. 5. Daily variation of the ionospheric delay of MSR (A) and PFISR (B) for KITSAT-1 in 2018. The ionospheric delay was calculated with the IRI-2016 model. MSR, Midland Space Radar; PFISR, Poker Flat Incoherent Scatter Radar; KITSAT, Korean Institute of Technology Satellite; IRI, international reference ionosphere.

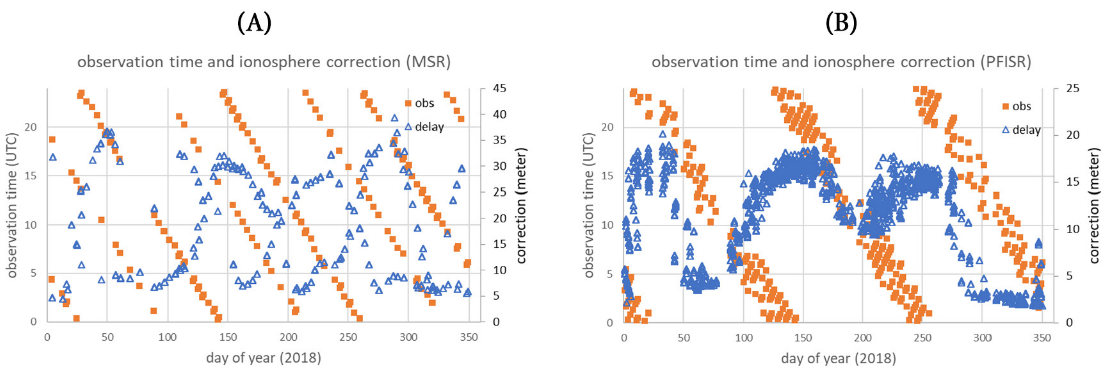

Fig. 6. Correlation between the observation time and the ionospheric correction of MSR (A) and PFISR (B) for KITSAT-1 in 2018. MSR, Midland Space Radar; PFISR, Poker Flat Incoherent Scatter Radar; KITSAT, Korean Institute of Technology Satellite.

correction than the observation season of the year.

The periodic variation of the observation time was caused by the orbital characteristics of KITSAT-1 and the geographical position of the radar station. The satellite tracking by radar is neither affected by the local time or the lighting condition of the Sun but the line of sight and the detectable range. We also confirmed the observation time variation of KITSAT-1 by the simulation results. Consequently, in order to estimate the precise orbital data from radar observations for space objects, the variation of the observation time due to the orbital characteristics needed to be considered for the ionospheric delay correction.

We confirmed the accuracy of the calculation of the ionospheric delay with the IRI 16 by comparing it with the GNSS data. The slant TEC (STEC) values for KITSAT-1 observation in 2018 on MSR and PFISR were compared with the IRI 16 model and the GNSS data. The STEC value with GNSS data was calculated with Vertical TEC using Single-Layer Model (SLM) (Schaer 1999). Fig. 7 show the STEC difference versus the observed elevation of KITSAT-1 and the STEC difference versus time in day. The range of variation in the differences of the STEC of MSR and PFISR are about 30 and 15 TEC units (TECU), respectively. The correlation between the STEC difference and the observed elevation angle is not clear (left sides of Fig. 7). The STEC differences in the daytime hours of MSR and PFISR are larger than STEC differences in the nighttime hours (right sides of Fig. 7). The range error for the radar by the ionosphere can be described as

$$d_I = \frac{K}{f^2} TEC \tag{2}$$

where the constant K is 40.3 m^3s^{-2} and f is the frequency of the radar (Jakowski et al. 2011). The maximum STEC difference for MSR and PFISR was 25 TECU and 15 TECU, respectively. Accordingly, the maximum range error by the accuracy of the ionospheric delay for MSR and PFISR was about 50 m and 30 m, respectively by Equation 2.

The ionospheric delay error by the difference of the IRI model and the GNSS data decreased with the higher frequency radar. If the frequency of the radar increased

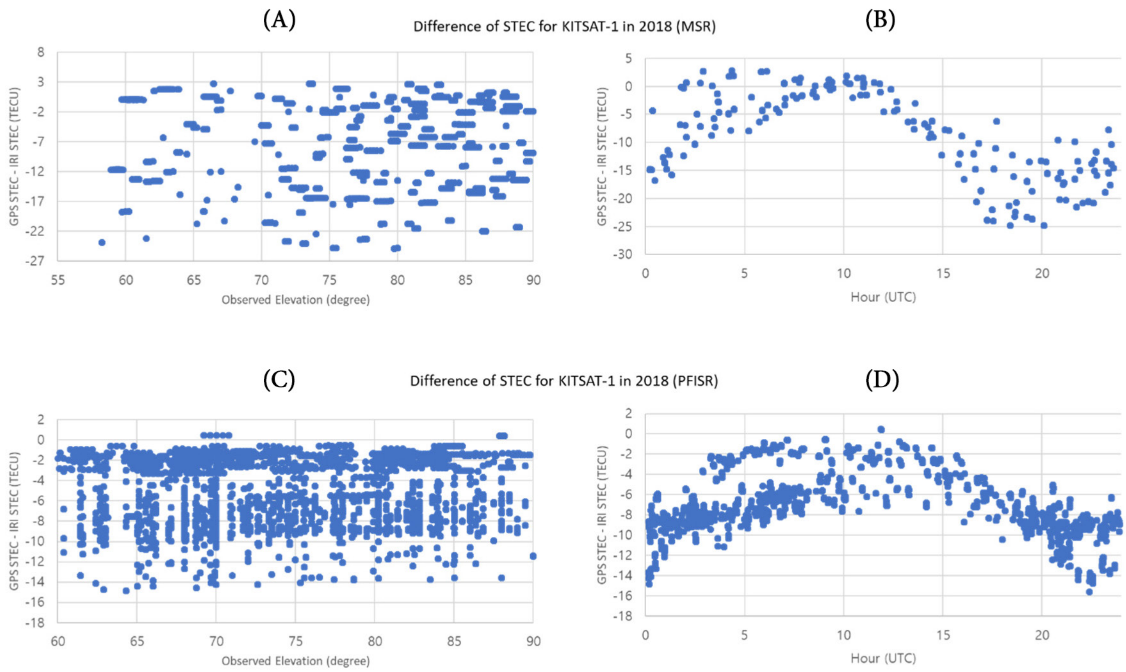

Fig. 7. STEC difference generated by IRI-2016 and GNSS of KITSAT-1 in 2018. The correlation between the difference and the observed altitude is not clear (A: MSR, C: PFISR). A daytime difference is larger than a nighttime difference (B: MSR, D: PFISR). IRI, international reference ionosphere; GNSS, Global Navigation Satellite System; KITSAT, Korean Institute of Technology Satellite; MSR, Midland Space Radar; PFISR, Poker Flat Incoherent Scatter Radar.

from 450 MHz to 2 GHz, the error can be decreased from 50 meter to about 2.5 meters for the previous case of MSR. We simply calculated the error for 2 GHz radar with Equation 2 and the maximum STEC difference for MSR. The error can be increased by the solar cycle and latitudinal position of the station or by an unexpected geomagnetic storm (Shi et al. 2019).

The IRI model was easier to use than the GNSS data for the operation of the radar for the real-time correction of the ionospheric effects. Even if the GNSS data can be used for near real-time correction, the model is also able to be used not only for error correction but also for predicting observation results. Therefore, both the IRI model and the GNSS data can be befittingly used by considering the system capability and the space weather condition.

3. ORBIT DETERMINATION TEST

3.1 Orbit Determination Process

We conducted the OD test for two scenarios. The OD period was selected as a weekly basis. It was based on the OD strategy of the OWL-Net. The estimated orbital ephemerides were compared with consecutive TLEs. There was no other comparison for KITSAT-1 which was an inactive satellite. The overall accuracy of TLE was known to be under 1 km for LEOs (Flohrer et al. 2008; Vallado et al. 2013). Therefore, the comparison results were not used for assessing the accuracy of the estimated orbit. Rather, they were referenced to confirm the reliability of the assessment.

The OD was conducted with the least-squares method to improve a priori, sequential filtering and fixed smoothing. We performed the test to find the appropriate initial orbit with two or three TLEs after the epoch of the first measurement from the radar. The initial position and velocity uncertainties were referenced to the accuracy of the TLE in previous studies. The geopotential harmonics (42 × 42), atmospheric drag (Jacchia-Roberts), lunisolar acceleration, and the solar pressure were considered as perturbing forces. A measurement model was referenced for previous studies for the LeoLabs radar (Griffith et al. 2019; LeoLabs n.d.). The system bias information providing by LeoLabs was used because any other in-situ information at the observation was not provided.

The estimated orbit was compared with the TLEs. The time close approach method was selected to smoothest possible switch between two TLE sets. Although the abnormal TLEs should be ignored, it depended on the gap of the published epoch between TLEs.

3.2 Orbit Determination Test with Double Stations

The OD results with the weekly basis strategy were compared with consecutive TLEs. The Root Mean Square (RMS) errors for 50 weeks are presented in the Radial, In-track, and Cross-track frames in Fig. 8. The In-track direction errors are dominant and the Radial direction errors are maintained under 10 m except 12th week. The Radial direction differences are smaller than the In-track and Cross-track direction differences. The In-track direction errors did not exceed 1,000 m except in the 12th week. As there was no observation data in the 12th week, the OD test was skipped. Among the 50 OD cases, the average number of arcs per week was about 10 and the minimum number of arcs per week was 4. The median value of the number of arcs per week was also 10. However, as shown in Fig. 6, the observation time over a certain period of time was found to be biased into specific local times for both stations. The median observation span for 2018 was 14 hours and 50% of the observation span exceed 22 hours. This meant that the arc observations were evenly acquired and 88% of the observations were conducted in 2 days.

3.3 Orbit Determination Test with Single Station

The OD test with the single radar station was also performed. Due to the similar position on the latitude with South Korea, MSR was selected as the single radar station. As shown in Fig. 1, the number of arcs and the number of the observation data points from MSR is much smaller than the results from PFISR. In Fig. 9, the overall RMS errors are almost 10 times larger than the results in Fig. 9. Considering the error range of TLEs, the comparison results in Figs. 8 and 9 only show consistency of the OD results with TLEs. In the 2nd, 5th, 10th, 11th, and 15th week, there were only single arc observations in MSR. The differences with TLEs for the single arc case were not significantly larger than those of the others. The various TLEs and the initial OD results were tested for the single arc cases. However, in the case of the single arc, the orbital estimation result made a larger error in orbit prediction (OP).

The OP test was performed to check the orbital consistency of the estimated orbits for KITSAT-1 with the single station. The estimated orbits were propagated for 2 days with consideration of the observation time span for KIT-

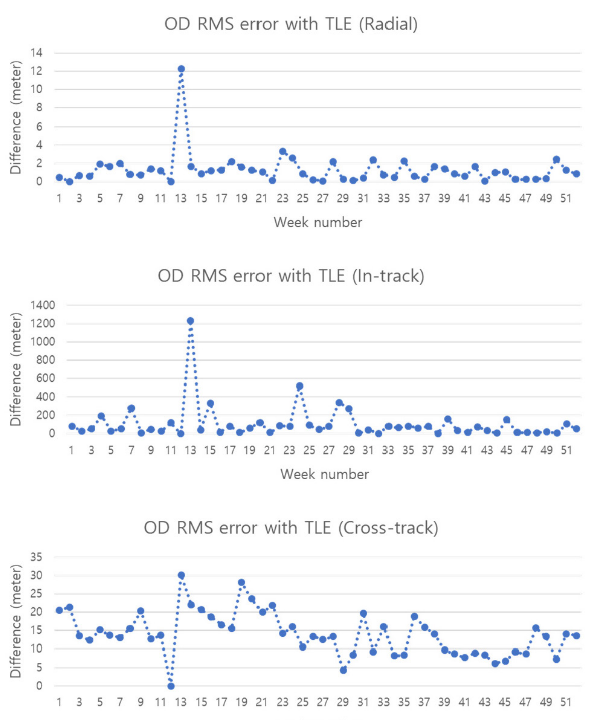

Fig. 8. RMS error with TLEs for the weekly basis orbit determination for KITSAT-1 in 2018. The RMS errors are presented in Radial, In-track, and Cross-track frames. Both MSR and PFISR measurements were used for OD. RMS, root mean square; TLE, two-line elements; KITSAT, Korean Institute of Technology Satellite; MSR, Midland Space Radar; PFISR, Poker Flat Incoherent Scatter Radar; OD, orbit determination.

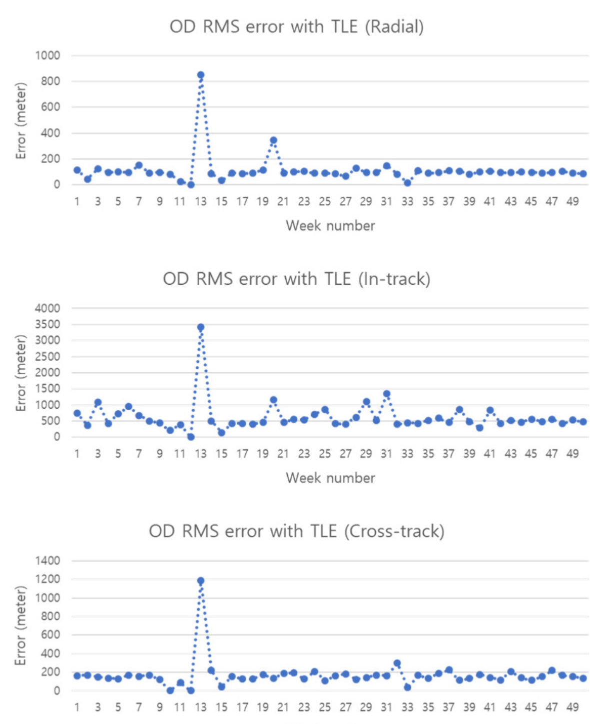

Fig. 9. RMS error with TLEs for the weekly basis orbit determination for KITSAT-1 in 2018. The RMS errors are presented in Radial, In-track, and Cross-track frames. Only the observation data from MSR was used. The overall errors were larger than the results with the observation data from both sites in Fig. 8. RMS, root mean square; TLE, two-line elements; KITSAT, Korean Institute of Technology Satellite; MSR, Midland Space Radar.

SAT-1 with a radar. The overall differences with TLEs of the OP showed in Fig. 10 are similar to the results of the OD. In the case of the single or double arc cases, the differences with TLEs of the OP were larger than others. Furthermore, the observation gap also decreased the OP performance for double arc cases. The OP RMS errors were also dependent on the quality of the TLE because of the shorter comparative period. The OD time spans were varied with the start and end time of the measurements ranging from a few minutes to several days for each case.

The OD test results showed the limitation of the single-radar station. The multiple stations can provide better OD results with the many more observation arc and measurements. And the multiple stations facilitate the facility operation when the observation schedules are overlapped. Had the single station been the only consideration, the latitudinal position of the station can affect the uncertainty of measurement due to the more active variation of the ionosphere.

4. SUMMARY

KITSAT-1 is the first launched Korean LEO satellite with the highest altitude and the smallest physical size. As the SSA capability of Korea has increased, the radar sensor is necessary to mitigate space hazards such as collision and re-entry situations on LEO. In this study, we analyzed the tracking results and the OD test results for KITSAT-1 in 2018 using MSR and PFISR operated by LeoLabs.

The total number of the observed arcs using MSR and PFISR was 157 and 349 times in 2018, respectively. The observation was conducted evenly for both stations. On the other hand, the range of variation in the range uncertainty of the observation using MSR was larger than that of using PFISR. And the range of variation in the correction values of MSR was under 50 m, while that of PFISR was under 25 m. The ionospheric delay was a dominant source of the correction.

The daily variation of the ionospheric delays of MSR and PFISR was confirmed. In the case of the observation using PFISR, the seasonal pattern was observed, while the yearly variation of the ionospheric delays for both stations was not clear. This was caused by the variation of the observation time due to the orbital characteristics of KITSAT-1 and the latitudinal position of the radar station. The IRI 16 model, which was used to correct the ionospheric delay in the radar observation by LeoLabs, was the latest model of the ionospheric model. We confirmed the accuracy of the IRI 16 with the GNSS data. The STEC values which were produced with the IRI-2016 model and GNSS data in 2018 for both stations were compared. The range of variation in the difference of the TEC of MSR was two times larger than that of PFISR. The difference of the GNSS data and the IRI 16 model could cause the maximum 50 m error for MSR. The differences of STEC were increased in the daytime hour.

The OD tests were performed for KITSAT-1. First, the OD with the measurements from both stations was performed on a weekly basis. The least-squares method for the initial orbit, and sequential filtering and smoothing were conducted for the cases for 50-weeks and the estimated orbits were compared with the consecutive TLEs. The observations for a single arc were evenly acquired and the observation spans did not exceed 2 days for 88% of the observation. With the exception of the 12th week due to the absence of the observation data, the In-track direction differences did not exceed 1,000 m. Second, the OD with the measurements from the single station, MSR, was performed on a weekly basis. The comparison results showed larger RMS differences with TLEs than the results using both stations. The OP results for 2 days showed similar results with the OD. The observations of MSR were made much less frequently than that with both stations and there were five single arc cases. In the case of the single arc, the OP results showed larger errors than the multiple arc case.

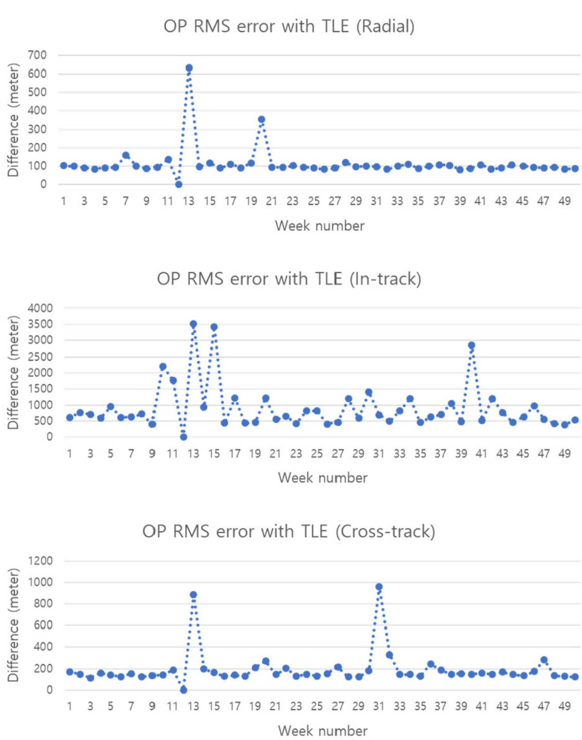

Fig. 10. RMS error with TLEs for the weekly basis orbit prediction for KITSAT-1 in 2018. The RMS errors are presented in Radial, In-track, and Cross-track frames. Only the observation data from MSR was used. RMS, root mean square; TLE, two-line elements; MSR, Midland Space Radar.

5. DISCUSSION

The ionospheric delay error is one of the sources that increases the range uncertainty of radar observation. In the case of the LeoLabs data, the observation data of MSR had larger ionospheric errors than that with PFISR due to the lower latitude of the station. As we described in chapter 2.4, the range error by the ionospheric delay can be decreased by under about 2.5 m with a higher frequency (~2 GHz) for KITSAT-1 observation with MSR in 2018. However, the system budget of the radar should also take into account the tracking limit and detectability of space objects.

In the analysis of the OD test, the single station case with the MSR data can provide the basis for estimating the performance of a single radar for KITSAT-1 in a domestic region. The orbital information can be maintained roughly within the accuracy of TLEs. The orbit estimation accuracy can be improved with the additional station, more precise measurements, and by assigning higher observation priority.

As discussed in this study, KITSAT-1 is an inactive satellite. Due to the accuracy of the TLE data, the accuracy of the estimated orbits was difficult to confirm with the data. However, the consistency of the estimated orbits by the weekly basis OD was confirmed for the TLE orbit class. However, the effect of the ionospheric delay model error for the orbit estimation result should be confirmed with the precise orbital ephemeris from the ILRS or onboard GPS data of the target satellite. And the error that occurs during strong solar activity or geomagnetic storms should also be checked to ensure stable operation of the radar as an SSA facility.

ACKNOWLEDGMENTS

The authors sincerely appreciate LeoLabs members for conducting the radar measurements and support for understanding and usage of the observation data. This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2019R1A6A3A01091743). And also, this study was supported by KASI (Korea Astronomy and Space Science Institute) grant 2020-1-854-03 (Project: Development of space object surveillance technology).

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