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Integrity Assessment and Verification Procedure of Angle-only Data for Low Earth Orbit Space Objects with Optical Wide-field PatroL-Network (OWL-Net)

Jin Choi[1†], Jung Hyun Jo[1], Sooyoung Kim[1], Hong-Suh Yim[1], Eun-Jung Choi[1], Dong-Goo Roh[1], Myung-Jin Kim[1], Jang-Hyun Park[1], Sungki Cho[1]
[1]Korea Astronomy and Space Science Institute, Daejeon 34055, Korea

The Optical Wide-field patroL-Network (OWL-Net) is a global optical network for Space Situational Awareness in Korea. The primary operational goal of the OWL-Net is to track Low Earth Orbit (LEO) satellites operated by Korea and to monitor the Geostationary Earth Orbit (GEO) region near the Korean peninsula. To obtain dense measurements on LEO tracking, the chopper system was adopted in the OWL-Net's back-end system. Dozens of angle-only measurements can be obtained for a single shot with the observation mode for LEO tracking. In previous work, the reduction process of the LEO tracking data was presented, along with the mechanical specification of the back-end system of the OWL-Net. In this research, we describe an integrity assessment method of time-position matching and verification of results from real observations of LEO satellites. The change rate of the angle of each streak in the shot was checked to assess the results of the matching process. The time error due to the chopper rotation motion was corrected after re-matching of time and position. The corrected measurements were compared with the simulated observation data, which were taken from the Consolidated Prediction File from the International Laser Ranging Service. The comparison results are presented in the In-track and Cross-track frame.

Keywords: OWL-Net, angle-only measurement, optical tracking, astrometry

1. INTRODUCTION

The Optical Wide-field patroL-Network (OWL-Net) is the first electro-optical tracking facility for Space Situational Awareness (SSA) in South Korea. Two primary goals of the OWL-Net were the tracking of Korean space objects in Low Earth Orbit (LEO) to maintain the orbital ephemeris, and the monitoring of the Geostationary Earth Orbit (GEO) region to protect Korean space assets in the orbit. The OWL-Net consisted of five global optical tracking facilities, and a headquarters in South Korea. The five facilities are located in Mongolia, Morocco, Israel, the United States, and South Korea. Each facility can make observations automatically on a daily schedule from the headquarters (Park et al., 2014; Kim et al., 2011). After completing the scheduled observations, the data reduction program makes observation reports of the astrometric or photometric results, according to its observational objectives, and sends them to headquarters.

The OWL-Net is operated with seven observation modes, defined by objectives and targets. The first and second modes are for the tracking of LEO satellites and the monitoring of the GEO region, respectively. The third and fourth modes are for high altitude space objects. The remaining three modes are for celestial bodies. Park et al. (2018) described the details for each observation mode. The seven observation modes are not distinguished by their operational method but by their purpose, therefore, a few observation modes work the same way but for other targets. Final reports also include specific results for the observational purposes. For example, in the case of the first and seventh observation mode, the observation method

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[†]**Corresponding Author**
Tel: +82-42-865-2080, E-mail: rutcome@kasi.re.kr
ORCID: https://orcid.org/0000-0002-2119-1956

and report form were the same; however, the targets were LEOs and an asteroid, respectively.

The OWL-Net system adopted a chopper in its back-end to make a dense observation for a single shot for LEOs and fast asteroids. Our system records several images during an observing opportunity, which we call shots, as the space object moves along its path. The astronomical Charge Coupled Device (CCD) usually needs an exposure and read-out time that is too long to get enough astrometric measurements for the orbit estimation in a single observation opportunity for LEO objects. Korean satellites in LEO, the main targets of the OWL-Net, can be observed for four minutes on average for a single observation opportunity. In contrast, the average interval between the opportunities was 400 minutes (Choi et al. 2018). The chopper blades chopped the streak of a shot into short streak-lets with a maximum speed of 50 Hz.

At the initial design phase, the system requirements of the OWL-Net were set to meet its goals. The time and position information accuracy were critical to estimating the orbits of target satellites (Choi et al. 2015; Son et al. 2015; Lee et al. 2017; Choi et al. 2018b). The Field of View (FOV) was set up at 1.1 deg x 1.1 deg by the consideration of the angular range of the Two Line Elements (TLE) error. The maximum speed of the mount was 20 deg/s to chase fast LEO objects. The observation time was recorded with one millisecond precision. To keep the precision of time information, each facility needed to utilize a Network Time Protocol (NTP) server with a Global Positioning System (GPS) antenna. The Site Operation System maintains the accuracy of time using the NTP server for both tracking the objects and recording the observation time. The system requirement of detection accuracy set up five arc-seconds full width half maximum with consideration for the observation environmental conditions (Park et al. 2014; Jo et al. 2015).

An optical tracking system is typically not the dedicated tracking system of the LEOs. A radar system is more useful than an optical tracking system to maintain the space catalog, owing to various advantages like observation conditions and the type of observation measurements (Choi et al. 2017; Choi et al. 2018a). A laser system, Satellite Laser Ranging (SLR), has been used to estimate precise orbits of space objects and partly used to track non-SLR dedicated space objects (Lim et al. 2018; Oh et al. 2017; Oh et al. 2018). However, an optical tracking system can be used for tracking or monitoring high altitude space objects. In the case of the optical tracking system for astrometric observations, the accuracy of observations has been averaging under five arc-seconds. A Baker-Nunn camera and Advanced Electro-Optical System (AEOS) has been used for LEO satellite tracking. The accuracy of metric data from those systems has varied from two arc seconds to more than ten arc seconds (Lambeck, 1968; Shoemaker, 2007). Another typical optical tracking system for high altitude objects, the Ground-Based Electro-Optical Deep Space Surveillance (GEODSS) system, has shown an accuracy of metric data from four to six arc seconds (Faccenda et al. 2003). The Raven telescope has relatively small optics and can be utilized for various tracking purposes. The accuracy of metric data of the Raven telescope for GPS satellites has been 2.2 arc seconds in Root Mean Squares (RMS) error (Shishido et al. 2004). As we mentioned above, the system requirement of detection accuracy of the OWL-Net was set at five arc seconds.

The time and position information from the OWL-Net is recorded separately during the exposure of the CCD (Park et al. 2013). The data reduction program for LEOs tracking performs the matching of the time and position information. However, the position information has errors caused by detection of bright sources (Park et al. 2015a). The inaccurate position information causes the wrong matching results of time and position, and the wrong matching results decrease the accuracy of the orbit estimation.

In this paper, we describe the integrity assessment method of matching the results of the time and position information from the OWL-Net. In addition, an error correction due to the motion of the chopper is also described. Finally, the corrected results are compared with simulated observation data from a precise orbit ephemeris as a verification procedure. By the comparison of the observed and the simulated data, the tracking accuracy of the OWL-Net for LEO space objects can be estimated for the present system configuration.

2. INTEGRITY ASSESSMENT OF OPTICAL TRACKING RESULT FOR LEO SPACE OBJECTS BY THE OWL-NET

The reduction program of the OWL-Net for LEOs tracking was described in Park et al. (2013). In the case of the OWL-Net for GEO tracking, the reduction process was separately built (Park et al. 2015b). When the scheduled observation started, the time tagging, chopper rotating, and shutter opening were simultaneously started by the operation program. The time tagger recorded not the absolute time but the relative elapsed time of the motion of the chopper. The absolute time of the motion of the chopper was calculated by adding the recorded elapsed time to the recorded absolute time, which was the operation system time at the time the tagger was started. In addition, the

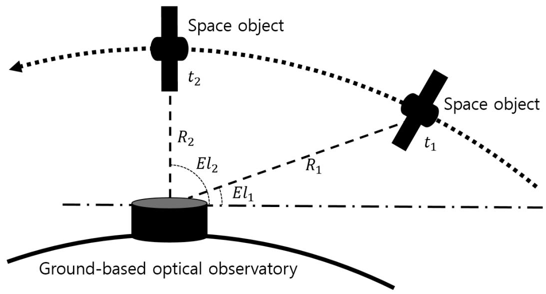

Fig. 1. Ground-based optical tracking for Low Earth Orbit (LEO) space object. A range, R_1 at a prior time (t_1) is decreased to a range, R_2 at a posterior time (t_2).

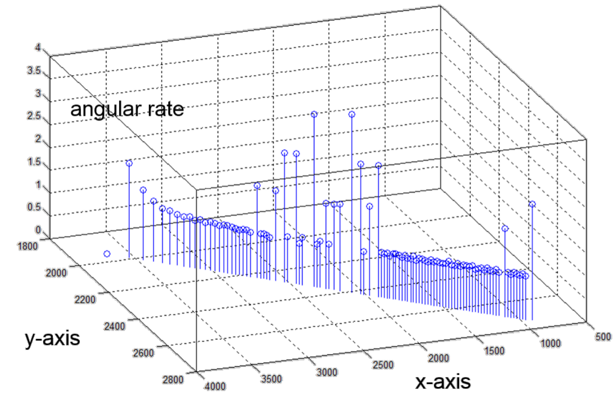

Fig. 2. Variation of angular rates of single image for a Low Earth Orbit (LEO) space object from the observation result by the OWL-Net. X and Y-axis is a surface of the Charge Coupled Device (CCD) and the vertical axis is an angular rate (pixel per ten millisecond) calculated by difference method. Incorrect time matching of the time and the position information results in an increase of the angular rates of an acceleration duration of the chopper (x-axis : 3000~4000, y-axis : 2000~2200). A few false detections make up the outliers.

position information of the streak-lets was achieved from the reduction of the image. After a coordinate correction with the solution of the World Coordinate System (WCS), the position of the streak-lets of the space object was calculated relative to the astrometric position of background stars. The final step is the matching of the time and position information. A ratio of the duration time of the chopper "open" and the length of a streak-let was used in the matching algorithm. The chopper was accelerated until the speed reached the set-up speed. Therefore, the lengths of the beginning part of the streak-lets were decreased as the chopper motion was accelerated.

Despite many efforts to distinguish only the streak-lets of space objects from the various bright sources of the obtained images by the OWL-Net, there were two main errors in the detection results (Park et al. 2016). First, the detection program can miss the detection of streak-lets due to the faintness of the signal or the background variation of the observed image. Second, the detection program can make false results by detecting other bright sources or operating incorrectly. These errors also can affect the matching results of time and position information. The matching error of time and position causes a bias of the observation time or an in-track direction error of the estimated orbit. The errors were not periodic or fully random and the matching results within a single image affected each other.

To assess the correctness of the matching results, a few physical conditions of the ground-based optical observation were considered. First, the OWL-Net is a ground-based optical tracking system; therefore, the observations are done on a topo-centric coordinate system. The space objects in LEO have almost circular orbits around the earth with almost constant linear velocity. Therefore, a range from the observer to the space object decreases as the elevation angle increases as shown in Fig. 1. This indicates that an angular rate changes proportionally with the elevation angle. However, the angular rate is almost constant within the FOV of the OWL-Net. We checked the variation of the angular rates by a difference method. The angular rate can be calculated by Eq. (1). The numerator is the angular distance between the position information on the CCD. The denominator is the difference of time. Because the chopper was accelerated with time, the recorded time durations and the length of the streak-lets were decreasing at the same rates. However, if the time and position information were matched incorrectly, the angular rates increase or decrease in the chopper acceleration duration as shown in Figs. 2 and 3. The detection error results in an outlier in the variation of the angular rate. Fig. 2 shows the angular rate variation on the surface of CCD. The x- and y-axis were identical with the axes of the CCD. The wrong matching results with the time and position information cause an increase of the angular rate up to about 0.2 pixels per millisecond. In the middle and end of the variation, the absences of detection are revealed as outliers. A few of the higher value points of the angular rate, above the average value, indicate that the length of the matched position information is longer than the normal case. In the case of outliers, there is a lack of data points before they appear. We confirmed the absence of points with the outliers produced by the difference method. In Fig. 3, the effect of the wrong matching results shows an acceleration and deceleration of the angular rate. The false detection errors also show outliers. By the natural motion of LEOs, the angular rates are constant in a single observation shot. When a certain streak-let was matched with shorter duration of time, the ratio of the length of the streak-let to the duration time was bigger than normal. Because the chopper speed was increased until it reached the set up speed, the angular rate looked to be a constant value when

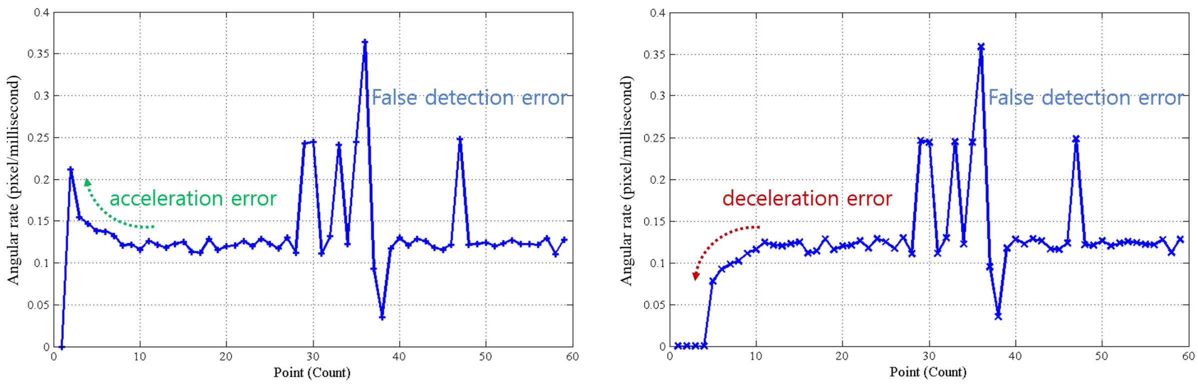

Fig. 3. Two types of errors for an incorrect matching of the time and position information of LEO space object tracking in a single image by the OWL-Net. The error results from the acceleration or deceleration of the angular rate. The outliers are caused by false detections. (Observation date: 21 Apr 2018, target: Envisat)

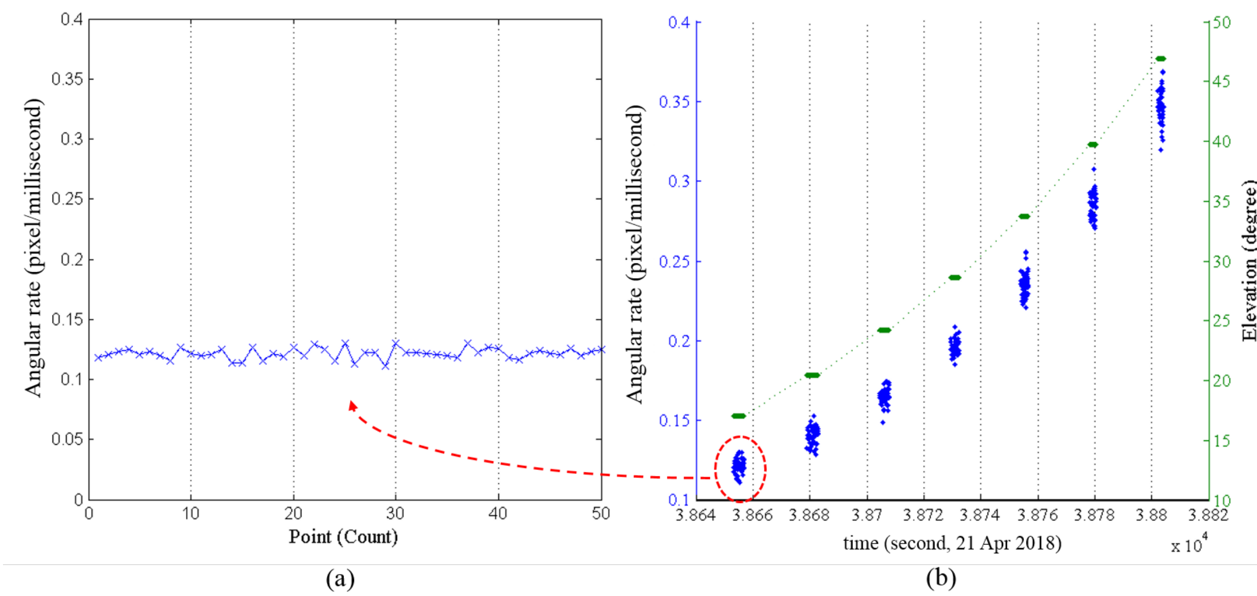

Fig. 4. Well-matched time and position information results. (a) In a single shot, the angular rate is almost constant when the time and position information of the observation for the LEO space object by the OWL-Net is matched correctly. (b) However, the angular rate gradually increases as the elevation angle increases in a single observation arc. (Observation date: 21 Apr 2018, target: Envisat)

the speed of the chopper reached the set up value. However, the time and position matching error still remained and accumulated to the end of the observation results in the single shot. The accumulated errors represent the time bias error in the orbit estimation process. The acceleration or deceleration points and the false detection outliers can be removed in the orbit estimation process. However, the estimation results show biased results in the In-track direction, because the rest of the points are also biased. The orbital error by biased estimation represents a larger error as the prediction time goes by.

$$\text{angular rate} = \sqrt{(y_2 - y_1)^2 + (x_2 - x_1)^2} \Big/ (t_2 - t_1) \quad (1)$$

Fig. 4 shows the angular rate variation in a single shot and a single observation arc when the time and position information are well matched. As shown in Fig. 4(a), the angular rate is almost constant in a single shot. However, it is not caused by a constant angular rate in a single observation arc but by a short exposure time for a single shot. The exposure time of a single shot was several seconds. The angular rate gradually increases as the elevation angle increases in a single observation arc. As the elevation angle increases, the angular rates for every single shot are spread out. This is caused by the higher angular rate and the consequent calculation error of the detection.

In Fig. 5, the green line represents the chopper blades. The CCD is the blue circle at the center of the back-end system. The time tagger photodiode shows as a red circle. When the chopper blade sweeps the surface of the CCD, the time tagger detects the motion of the chopper and records a duration time. However, the time-tagger photodiode sensor as shown in Fig. 5 is exactly opposite the CCD and detects the blades at the instant the chopper blades pass the center of the CCD. Thus, the recorded observation time is incorrect when the detected streak-let is not located on the center of the CCD. The time error for the motion of the chopper is smaller when the chopper rapidly rotates. Therefore, the time error during the acceleration period is bigger than the time error for a fixed speed period.

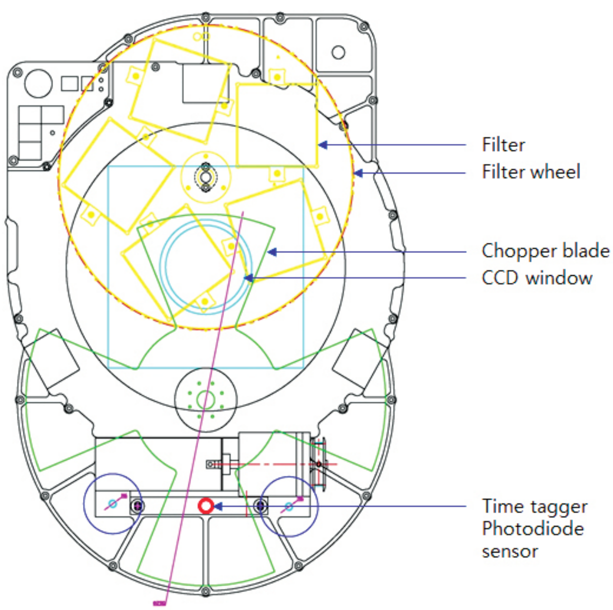

Fig. 5. Diagram of the back-end system of the OWL-Net. The chopper blades are marked with a green line. The time tagger photodiode sensor (red circle) is opposite the center of the CCD (sky blue circle).

The time error by the chopper motion is a considerable source of time accuracy error considering the system requirement of the OWL-Net. Fig. 6 shows the maximum time error by the chopper rotation speed. When the chopper rotation speed is 50 Hz, the maximum time error is about 2.8 millisecond. This indicates that the time error by the chopper motion must be corrected to measure the accurate time of the observation for LEOs by the OWL-Net. However, the chopper is accelerated from 0 Hz to set up maximum speed. Therefore, beginning parts of the streak-lets have the possibility of creating a bigger time error with the slower chopper speed. Fig. 7 shows the effects of the correction for the chopper rotation. A few errors in R.A. and a slanted tendency in Dec. are corrected. The corrected scales of the error for R.A. and Dec. depend on the direction of the motion of the satellites, the rotation angle of the CCD, and the range from station to satellites. This error also increases the time error for the orbit estimation process. However, the errors by the chopper motion in a single arc cannot be

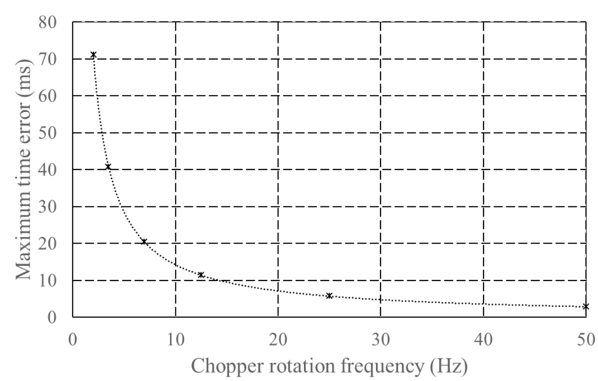

Fig. 6. Maximum time error by chopper rotation speed. When the chopper rotation speed is 50 Hz, the maximum time error is about 2.8 ms.

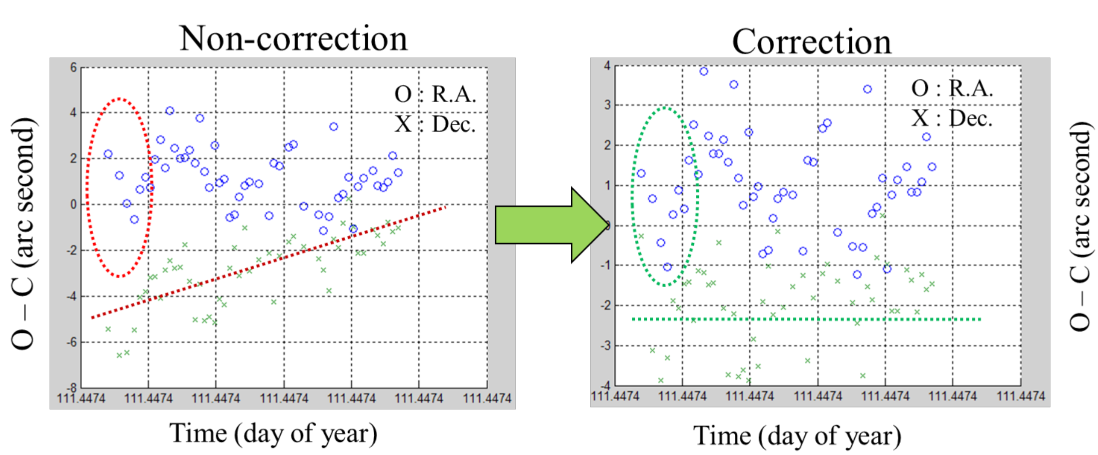

Fig. 7. Time error by the chopper motion is corrected for a single shot. There are a few larger errors and inclination of the trend before the correction (left).

Table 1. Specification of ENVISAT

SATCAT ID	27386
Dry mass	7,900 kg
Dimensions	26 x 10 x 5 m
Altitude	770 km
Inclination	98.4 deg
Period	100.16 minutes

modeled owing to the observational environment. The error under one millisecond was neglected owing to the order of magnitude of the time recording of the OWL-Net.

$$\theta = \tan^{-1}\frac{\triangle X}{(L+\triangle Y)}, \quad T = a \times \theta \qquad (2)$$

The time error (T) was calculated by multiplying the angle of the streak-let (θ) and the chopper rotation speed at that time (a), as in Eq. (2). The angle of the streak-let indicated the angle between the position of the streak-let on the surface of the CCD and the center of the CCD (ΔX, ΔY). In this calculation, the length from the center of the chopper to the CCD (L) should be considered. The position of the streak-let on the surface of the CCD was determined by the pixel number of the CCD. At this point, the rotation angle of the CCD, which is determined by the pointing direction of the optics, was also considered. The chopper rotation speed at the observation time was not recorded in the operation system. The duration time of the opening and closing motion of the chopper were recorded by the time tagger. If we could match the time and position correctly, the chopper rotation speed for each streak-let would be calculated from the duration time of the motion of the chopper. Even if the chopper rotation speed, calculated using the duration time, were an average speed, the calculated time difference would be negligible.

3. VERIFICATION PROCEDURE AND RESULTS

In this research, we verified an actual optical measurement by comparing it with simulated observational data that was made using a precise orbital ephemeris. TLE is publicly released orbital information, but it is not accurate enough to use for verification of the optical observation system. In general, the Global Positioning System (GPS) data are very accurate and sufficient for verification of the observation system. However, GPS data are only provided for specific satellites when the satellites are operational. Another significantly precise orbital ephemeris is the Consolidated Prediction Format (CPF) data. The CPF data are the official International Laser Ranging Service (ILRS) format for satellite predictions for a satellite laser ranging (SLR) system. The accuracy of the CPF data is within a few tens of meters. The CPF data are easily accessible by a website and is also provided for a few inactive satellites. We used daily CPF files to reduce the error for the prediction process.

In previous research for the verification of astrometric data from the OWL-Net, Cryosat-2 and KOMPSAT-5 were used as a comparison (Choi et al. 2018). KOMPSAT-5 is an operational satellite and the precise orbit ephemeris using onboard GPS data has been provided. Cryosat-2 is also in operation and CPF data can be downloaded via the website. In the case of an operational satellite, the CPF data should be utilized by confirming the maneuver dates of the target. Another constraint on selecting the comparison data set was the seasonal variation of the optical observation opportunity with the OWL-net. KOMPSAT-5 and Cryosat-2 were only possible to observe from October to March, and from April to September, respectively. Therefore, we selected another comparison, ENVISAT. ENVISAT is an inactive satellite and can be observed with the OWL-Net all through the year.

The OWL-Net is a ground-based optical tracking network. Therefore, the observations were performed in the topocentric coordinate system. The astrometric position of the target was determined with the position of background stars in the observed images. The astrometric positions of stars in the star catalog used the Earth Centered Inertial (ECI) J2000.0 frame as the coordinate system. The positions of the satellites were expressed in terms of right ascension and declination. When the position of space objects in this frame was compared with the comparison data, a coordinate singularity could occur when the position of a space object was near the pole of declination. The singularity can be removed by selecting a different frame. In this research, we chose an In-track and Cross-track (IC) frame. In the IC frame, the origin point is one of the positions of the observation and calculation. Because the optical observation did not provide the range information, the comparison was only possible on a two-dimension frame. The comparison results were expressed in arc seconds. The range scale effect was neglected because the range information was not provided from the optical tracking observation.

An appropriate observation model was required to perform the observation simulation. In this research, we considered the light travel time, as well as annual and diurnal aberration. The stellar parallax or refraction was negligible when considering how to determine the position of the space object. In the case of parallaxes refraction of a space object, the range information was needed to calculate it and the amount of the refraction was not significant (Veis 1963).

For the verification procedure of the optical tracking measurements, the orbit estimation was not considered. Fig. 8 shows the comparison procedure used for the optical observation data from the OWL-Net and the external precise orbital ephemeris. First, the detection error and the matching error of time and position were corrected. The chopper rotation effect was also considered. In parallel, the position information from the precise orbital ephemeris was used to make the simulated observation data with a few simulation conditions. After comparing the actual observation data and the simulated data, the result of the ECI frame was finally converted to the result of the IC frame.

ENVISAT observation data were sampled for a test of the verification procedure of the optical tracking data for LEOs with the OWL-Net. Table 2 is a summary of the sampled observations. We selected the observation data for different dates and sites. On average, about 50 points were achieved for each shot. A few images did not provide any observation data due to the bad quality of the image or a reduction program error.

Comparison results are shown in Fig. 9 and Fig. 10. Fig. 9 shows the In-track versus Cross-track differences obtained using data from three OWL-Net stations. The difference ranges of the In-track results do not exceeded ± ten arc seconds for all cases. Except for the Cross-track difference from OWL-Net 4, the difference ranges of the Cross-track are ± five arc seconds. Owing to the bad quality of a few images, the Cross-track difference of the OWL-Net 4 shows a range twice as large as the results from the other two sites. Fig. 10 is a box and whisker graph for the In-track difference. The average of the In-track difference is one arc second. The medians of the In-track difference are almost the same as the average values and the length of the wings are similar to each other with sub-arc second difference.

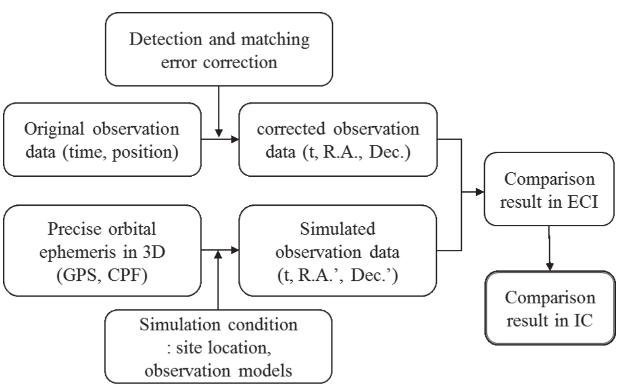

Fig. 8. Flow chart for the procedure of comparison for the optical observation data from the OWL-Net and the precise orbital ephemeris from external sources.

The range of the LEOs from the ground varied by elevation. When the range was varied from 550 km to 2000 km, one km error can be converted to an astrometric scale error of 105 to 375 arc seconds. Therefore, one arc second error represented an equivalent range error of 9.52 to 2.6 meters (Choi et al. 2018b). However, the projection effect by the elevation should be considered when converting an astrometric scale error to a range scale error.

Not every point of the comparison results had the same weight. The reason for the differences was not only the accuracy of the observation system but also the image quality, detection program error, weather conditions at that time, and the other sources of light. The observation system accuracy from the comparison between the optical observation result and the precise orbital information was not deterministic. Therefore, a complete validation of the optical observation system needs to be performed over a

Table 2. Observation summary for verification procedure test

Site	Date (yyyy-mm-dd)	duration (minute)	Number of shot	Number of point
KR (5)	2018-04-21	2.5	6	302
Israel (3)	2018-08-13	3.7	6	308
US (4)	2018-09-22	7.1	13	698

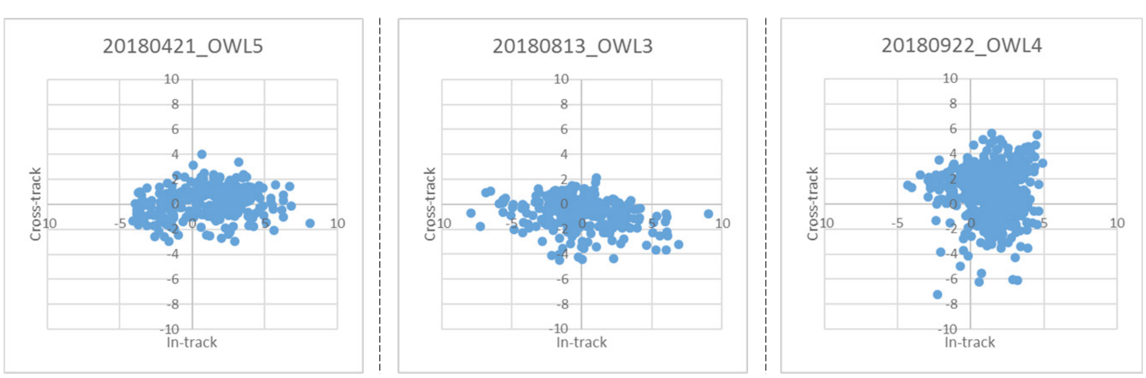

Fig. 9. In-track versus Cross-track results. For OWL-Net 5 and 3, the In-track differences are larger than the Cross-track differences. The Cross-track difference for OWL-Net 4 is larger than the results from other sites due to the bad quality of a few images.

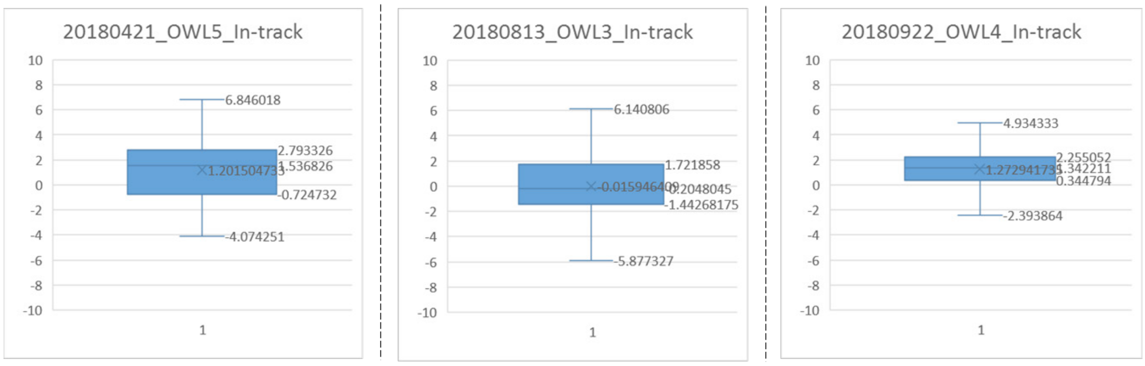

Fig. 10. Box and whisker graph for the In-track differences. The average of the In-track difference is one arc second. The range of the In-track difference does not exceeded ± six arc seconds.

full year by season, weather conditions, and mechanical maintenance.

4. DISCUSSION

Optical tracking is the traditional and essential way to observe space objects in earth orbit. The OWL-Net is the first Korean Space Situational Awareness (SSA) facility to track LEOs and monitor the GEO region. One of the main purposes of the OWL-Net was maintaining the orbital ephemeris of Korean LEOs. The OWL-Net system adopted the chopper system to acquire many observation points from a single shot. The matching of the recorded time and the angular position from the reduction of the observed image affected the accuracy of the orbit estimation directly. An accurate timekeeping system was mandatory to maintain the quality of the orbit estimation results. In the case of the optical tracking system, the image reduction process was needed to get the position information of the observation targets. Therefore, the precision of the detection software and the quality of the image was important to maintain the accuracy of the orbit estimation results. However, many environmental parameters like weather conditions also affect the reduction results of the image.

We attempted to assess the matching of the time and position information by confirming the angular rate with the difference method. After the correction of the detection and matching results, well-matched results were achieved. The assessment method of this research was based on the orbital motion by natural and geometrical specifications of the ground-based observation of the space objects. However, the detection ability of the reduction program was very critical and it was deeply connected with weather conditions or other observation environments. Therefore, another method to avoid the limit of our detection ability is required for better reduction results.

The procedure for the verification was introduced in section 3. An observation model for the ground-based optical tracking was developed to simulate the observation points with the precise orbital information. The light travel time, as well as annual and diurnal aberrations, was considered for the simulation. The refractions related to the stellar motion were neglected because the position of the space objects was determined from the background stars in the image. The parallax refraction was also neglected because the optical tracking results did not include the range information. However, parallax refraction might need to be considered during the orbit estimation process.

We conducted the verification test for the optical tracking results of ENVISAT with the observation data from the OWL-Net 3, 4, and 5. The comparison differences were presented in the In-track and Cross-track frame instead of R.A. and Dec. frame to avoid the coordinate singularity problem near the pole of the declination. As a result, the average of the comparison results for the In-track difference was one arc second and the ranges of the In-track differences did not exceed ± ten arc seconds. In the box and whisker graph for the comparison results for the In-track difference, the range of differences was about ten arc seconds. The comparison results for each observation point were affected not only by the system accuracy but also by the observation conditions. From a statistical perspective, the comparison results were in agreement with the system design accuracy of the OWL-Net.

Finally, assessment and verification of the optical tracking results for LEOs from the OWL-Net were introduced and a few results were presented. The comparison results can be affected by many environmental parameters, therefore, a long-term analysis is required for over a full year. Moreover, not only is it necessary to extend the verification procedure for the observation results with better statistics, but it is mandatory to validate the overall accuracy of the OWL-Net by better estimations of the orbits.

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