Short-arc orbit determination results and space debris test observation of the OWL-Net

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ABSTRACT

Korea Astronomy and Space Science Institute had developed the Optical Wide-field patroL-Network (OWL-Net) for maintaining the domestic Low Earth Orbit satellites' ephemeris and monitoring Geostationary Earth Orbit region. It also can be used to observe space debris. The orbit determination process was planned with batch least square orbit estimator for every week. The optical tracking window is very narrow, several times per week. Sequential-batch type estimation strategy was attempted for more reliable orbit prediction. We compared the test operation results with Two Line Elements and CPF files to validate the system. This results can be used to estimate the performance of the OWL-Net operations. And also we had observation of the Astro-H debris. We got the dozens of photometric data of the Astro-H debris main part for a few seconds with the chopper system.

1. INTRODUCTION

Optical tracking system have been used to observe various space objects from the beginning of space development. The optical tracking system were formerly used for not only identification but also orbit determination. The Baker-Nunn camera is a representative classical optical tracking system. In recent years, radar systems are mainly used for orbit determination of Low Earth Orbit (LEO) objects of Space Situational Awareness (SSA). On the other hands, Geostationary Earth Orbit (GEO) objects are still tracked by the optical tracking systems. GEODSS is being used for the main purpose of Geostationary Earth Orbit (GEO) object tracking [1]. Since only angle measurements are provided and the viewing conditions are very harsh, the optical tracking has been focused on observing deep space objects or natural objects as other observation systems are developed. But the optical tracking has advantages as a passive observation system.

Korea Astronomy and Space Science Institute (KASI) had been developed the Optical Wide-field patroL-Network (OWL-Net) since 2010. The main goal of the OWL-Net is maintaining the domestic Low Earth Orbit satellites' ephemeris and monitoring Geostationary Earth Orbit region. The optical tracking station was installed in five sites in Mongolia, Morocco, Israel, USA and South Korea [2]. The OWL-Net is fully automatic observation system with headquarter in South Korea. Each stations are controlled by Site Operation System (SOS) and received daily schedule from the headquarter.

The OWL-Net applied a chopper system to acquire a large number of observation points from a single image [3]. The chopped streaks are aligned with the recorded time information using the its angular acceleration. The maximum speed of the chopper system is 50Hz, which can be converted to 0.02s. The number of points exceeds 400 through several exposures per one arc. It depends on the duration time of arc for satisfying observation condition as geometric condition. Average observation duration is only 5-10 minutes. It is a very short time compared to the entire one arc. Also, the optical tracking chance is rare than other systems. The number of observation chance of LEO satellites is under 3 times per day with the OWL-Net. Even if a large number of observation points are acquired in one shot, only some of the information in the entire trajectory is obtained. Therefore, we attempted to solve this orbit estimation problem by short-arc with sparse data orbit estimation strategy.

2. Measurement calibration and validation

The optical tracking data from the OWL-Net was verified with the precise ephemeris file, Consolidated Prediction Format (CPF). We selected Cryosat-2 as validation target. Its semi-major axis is about 720km, similar with South Korean domestic LEO satellites. OWL-Net automatically generates the final data, including time and angular position information for each targets. Park et al. [4] lists some error sources of the OWL-Net tracking data with calibration procedure. Additional calibration procedure using rate of angular velocity was applied after that.

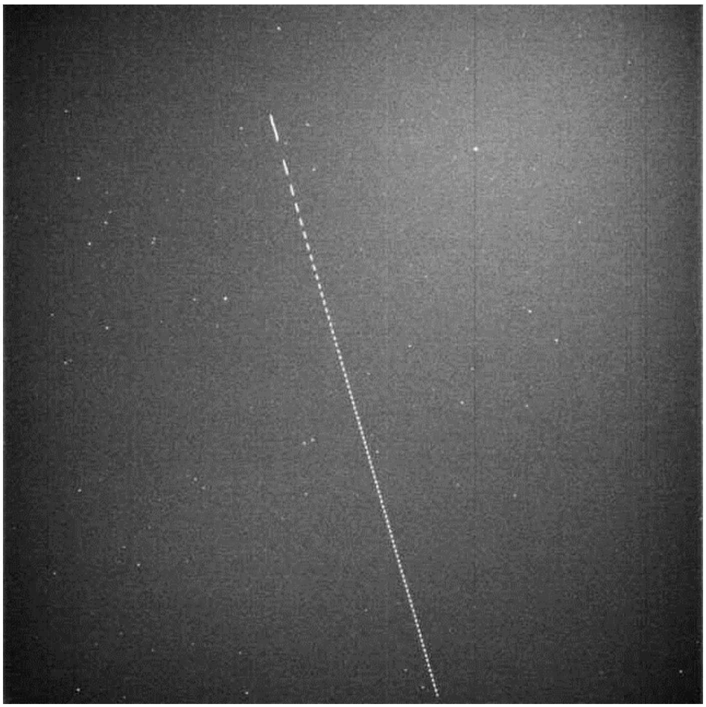

Fig. 1. Observation image of Cryosat-2 on 1st Jun. 2016 in Israel site of the OWL-Net

The validation target observation was done from 2nd to 6th of Jun. 2016. Cryosat-2 has Laser Retro-Reflector (LRR) for tracking of Satellite Laser Ranging (SLR) system. Totally five passes were got for six days in Israel station. Table 1. describe the summary of this validation observation. The observation data calibration procedure was done for deleting the outliers.

Tab. 1. Observation summary of Cryosat-2 in Jun. 2016

Pass number	Number of shot	Number of data	Date and Time (UTC)
1	5	360	02 Jun 2016 00:34:47.695 ~ 02 Jun 2016 00:36:33.483
2	3	346	02 Jun 2016 23:44:46.720 ~ 02 Jun 2016 23:45:44.878
3	5	429	04 Jun 2016 00:32:22.475 ~ 04 Jun 2016 00:33:28.656
4	4	385	06 Jun 2016 00:29:47.398 ~ 06 Jun 2016 00:30:54.714
5	4	409	06 Jun 2016 23:39:47.541 ~ 06 Jun 2016 23:40:44.139

The calibrated measurements were validated using the CPF file. The CPF file was downloaded from ILRS website. We considered the observation model of the optical tracking. Timing bias or variation were not taken into account in this step. Fig. 2. shows the difference of the simulated measurements using the CPF file and the real measurements from Israel station of the OWL-Net in 1st Jun. 2016.

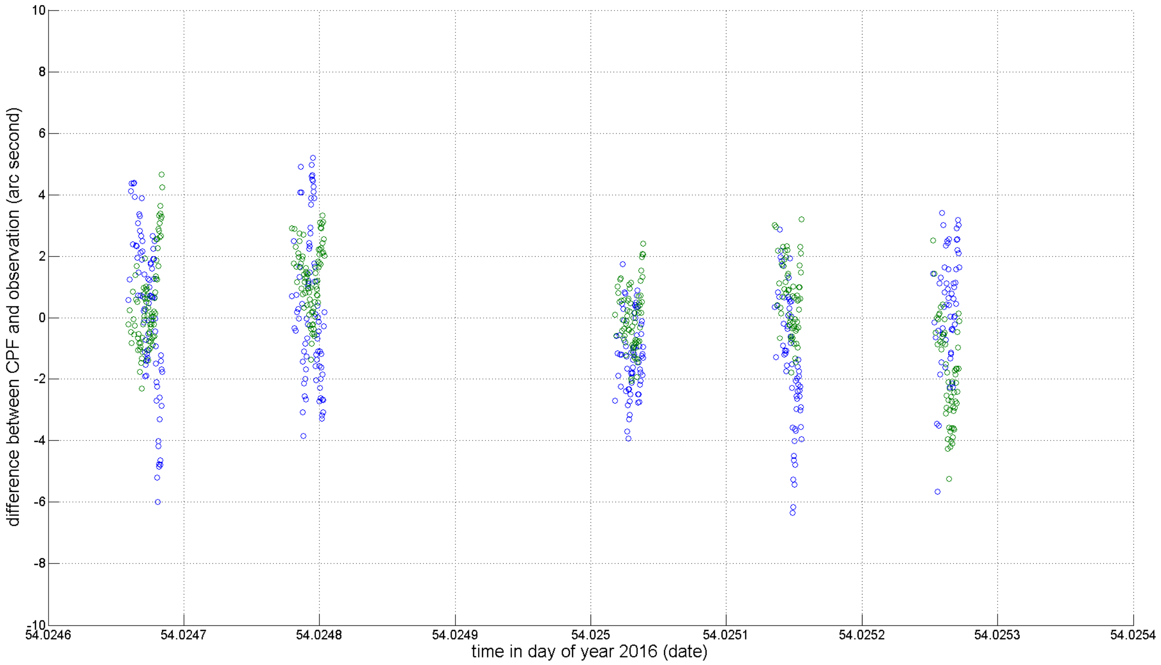

Fig. 2. Difference of the CPF and observed measurements of Cryosat-2 in 1st Jun. 2016
(blue dot: R.A., Green dot: Dec.)

We got five shots during only one minute in 1st Jun. 2016. And each shot includes averagely 70 points. Mean difference of the R.A. and Dec. is -0.3 and 0.2 arc seconds, respectively. The RMS error of R.A. is 2.3 arc seconds, whereas the RMS error of Dec. is 1.6 arc seconds. The variance of the difference is expected to be related to the observational seeing condition. The observational seeing could be varied due to not only the atmospheric condition but also other reasons like telescope mount movement. The differences are not spread as Gaussian normal distribution. The modes for R.A. and Dec. are -1.2 and 0.5 arc seconds, respectively. The CPF information does not represent perfect true orbit. Also, the observation measurements are not completely fitted with true orbit. However, it is necessary to consider the non-Gaussian variation of the measurement for the accuracy of this orbit estimation.

3. Short-arc orbit estimation with the OWL-Net

In general, short-arc orbit determination issue has been discussed to find initial orbit with uncorrelated targets [5]. The orbit estimation with the optical tracking system for LEOs is short-arc and sparse data issue. In case of the orbit estimation for the SLR system, it deals with similar problems with very precise level. Several batch techniques, such as particle filtering, and genetic algorithms, have been demonstrated for sparse orbit estimation cases. However, a complicated tuning process was suggested with as frequent observation as possible for practical solution [6]. Ning et al. [7] also suggested drag coefficient estimation with various time span to solve short arc orbit estimation. It was definitely shown that more frequent estimation of drag coefficient guaranteed more precise estimation results. Landsat 4 case shows that continuous estimated drag coefficient with sequential filter are relatively more varied than those of batch filter [8].

We focused more on the orbit estimation strategy. Sang et al. [9] described debris orbit predictions using sparse tracking data from single SLR station. They suggested 2 passes of tracking data over 24h for 1-day orbit prediction accuracy better than 20 arc seconds. The short-arc orbit estimation study using the optical tracking system was also done by Bennett et al. [10]. The optical tracking data for only five seconds of length for several days were used to estimation test. The observation chance was only one or two times of a day. The angle-only test results showed good orbit predictions with five seconds data with ballistic coefficient estimation. The ballistic coefficient estimated from historical Two Line Elements (TLEs) data by Joint Space Operation Center (JSpOC) [11]. Genova et al. [12] described another estimation strategy for planetary mission spacecraft, BepiColombo, the European Space Agency (ESA) mission to Mercury. Batch-sequential method and Multi-arc method used parameter two categories, local and global parameter by dependency of single or multi arc. Latter batch-sequential method is more stable than classic Multi-arc method by using sequential updates of the global estimated parameters.

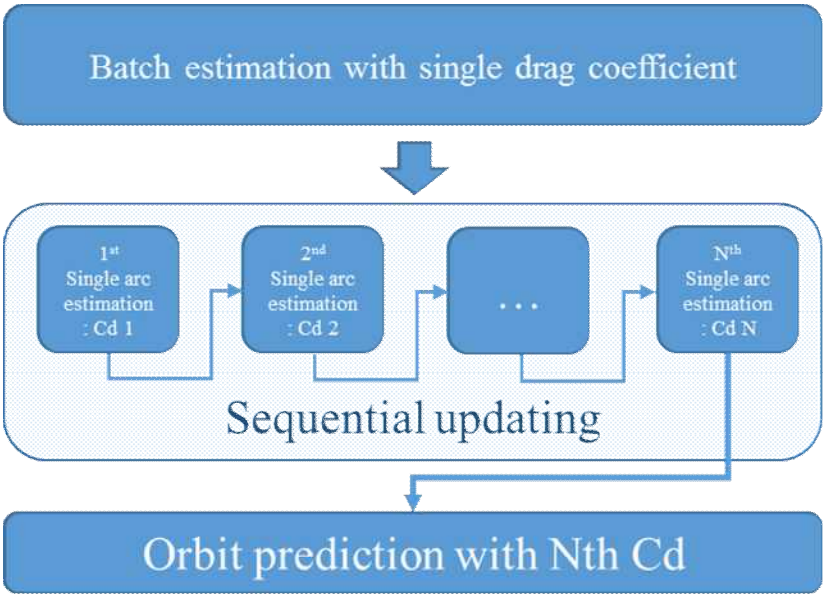

Fig. 3. Sequential-batch orbit improvement flow using the optical tracking data

The optical observations of the OWL-Net for LEOs were performed sparsely with short-arcs and high rate condition. There was no "global parameter" for entire estimation duration. However, drag coefficient or ballistic coefficient is not fixed coefficient but empirical variable for un-modeled status. In addition, observation time span of the short arc is very limited for entire observation period. Therefore, we attempt to improve orbit estimation results with sequential-batch orbit improvement strategy. Fig. 3. shows sequential-batch orbit improvement flow. First, we executed batch style estimation with single drag coefficient estimation for entire observation period. Second, estimated orbital solution was re-estimated for each single arcs with sequential update. Finally, improved state vectors and drag coefficients were used to predict the following observations.

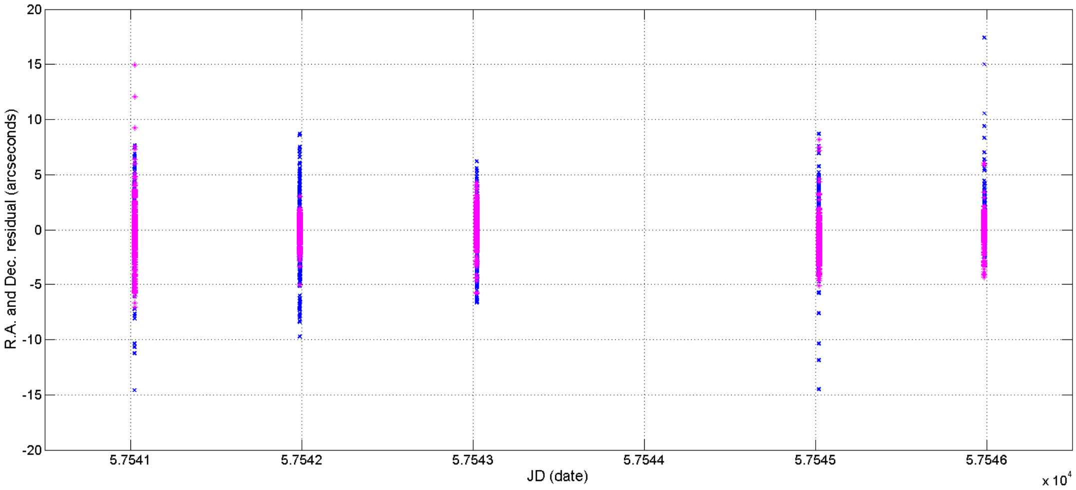

Fig. 4. Difference between the orbital solution data and CPF data by ESA

The sequential-batch estimation strategy for optical tracking system is based on the specificity of the optical tracking observation. As we described above, optical tracking data was sparsely distributed and tracked for too short-arc. It is very limited condition for orbit estimation. Typical 4h, 8h approaches for drag coefficient estimation could not be applied with too short and sparse data. The sequential batch estimation strategy was applied to improve the orbit prediction robustness with this difficulty. Fig. 4 shows comparison results of estimated orbit simulation measurements and CPF data by ESA. The observation time span was almost one or two day. Besides, observation time for each arc was about 2-3 minutes on average.

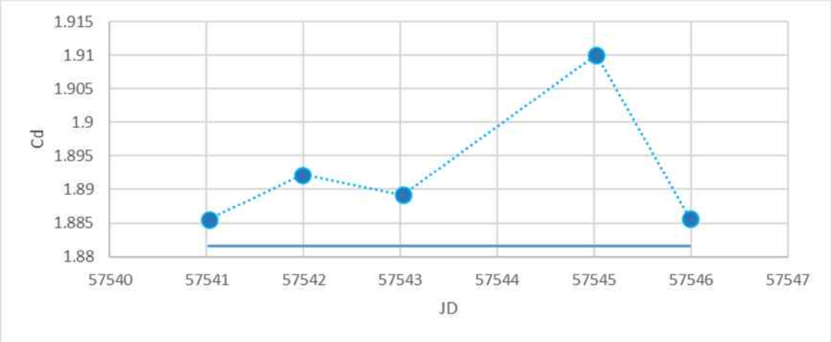

Fig. 5. Estimated drag coefficient of batch and sequential-batch (line: batch, dots: sequential-batch)

Fig. 5. Shows the estimated drag coefficient variation of batch and sequential-batch estimation results. The batch estimation result is smaller than average value of sequential-batch estimation results. In 6th June, JD 57545, drag coefficient value from sequential-batch estimation shows bigger than one's for other days. We were able to discover the possibility of this unusual result. The K-index, as can be thought geomagnetic storm alert, was increased from noon at 5th June to noon at 6th June. Earth magnetic storms can increase atmospheric density when it blows to the earth.

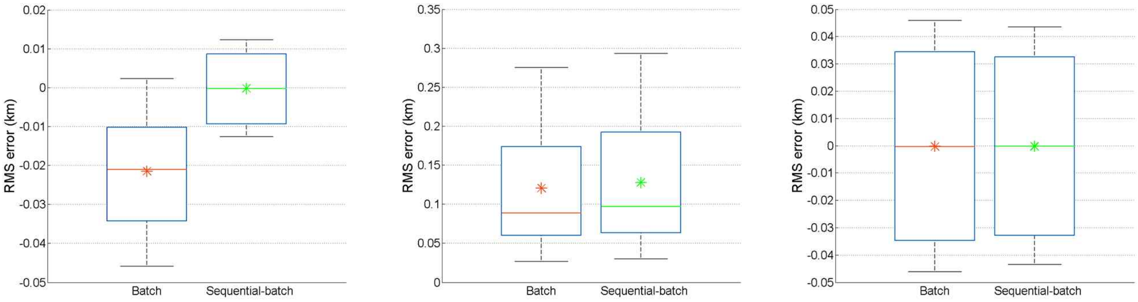

Fig. 6. Comparison of batch and sequential-batch estimation OP for 7 days with CPF from ESA

The orbit prediction for 7 days after last observation date was compared with the CPF data from ESA. Fig. 6. shows Radial, In-track, and Cross-track results by the batch and the sequential batch estimation, respectively. In-track direction error is increased up to 120 meter in RMS error for both results. However, radial direction error mean value was decreased to zero in RMS error. The width of error also decreased. For cross-track direction error, it was slightly decreased. Improvement in orbit prediction is small, but it is useful to understand and predict the orbit with sequentially updated drag coefficient information.

4. Space debris test observation

We performed test observation for space debris using the OWL-Net. Space debris including retired or broken down satellites are not possible to connect via established ground antenna system. The optical tracking system can make observation under sufficient tracking conditions like their brightness. ASTRO-H, New X-ray Telescope (NeXT) broke up at 26th March, 2016. The OWL-Net system in Israel was used to attempt test observation of the

ASTRO-H on 7th April, 2016. Average exposure time is 3.45 seconds. Maximum chopper speed was 50Hz to get five successful shots.

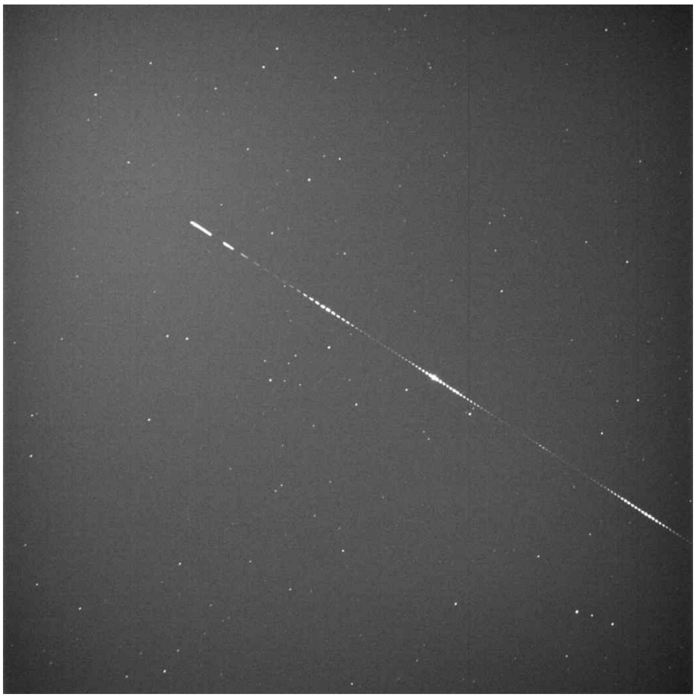

Fig. 7. Astro-H observation image at 17:56:37 UTC on 7th April 2016

Fig. 4. shows the sample image of ASTRO-H on 7th April, 2016. The observed streak-lets shows brightness variation. We attempt to find rotation period using five shots after brightness correction for phase angle and range. The rotation period was analyzed by the peak to peak variation method. Determined rotation period was 5.20 seconds, and it was well matched with JAXA's presentation, 5.22 seconds [13].

The OWL-Net system may be used to make tracking not only for domestic LEOs but also for more space debris in event situation. Especially, the observation modes for LEOs, GEOs and natural body are under tested using longitudinally well distributed network.

5. Summary and future work

The OWL-Net, the optical tracking network, is under test operation phase now. We made the test observation to verify observation accuracy and calibrate analyzed error sources. The CAL/VAL target was selected as Cryosat-2 to its visibility of the OWL-Net and observation condition. The difference between the CPF data and observed measurements were under 5 arc seconds in RMS error on average. However, due to the seeing condition, differences were not normally distributed.

The optical tracking measurements are very short-arc and sparse data. We attempt to use sequential-batch estimation strategy for robust orbit prediction. The estimated orbital solution and covariance information using the entire observation data was used as initial information for the sequential-batch process. The sequential-batch process was considered to find more precise drag coefficient for too short and sparse data. The sequential-batch estimation strategy can improve the orbit prediction robustness a little bit. However, it can be used to understand and predict the orbit using geomagnetic storm information for changes in atmospheric resistance.

Space debris test observation was performed to broken down LEO satellite. The Astro-H was observed in the OWL-Net Israel station. We got five successful shots with maximum 50 Hz of chopping speed. Determined rotation period was validated with JAXA's result. The OWL-Net system will be utilized to observe space debris on LEO and also high altitude.

6. REFERENCES

1. Michael A. Shoemaker and Lewis E. Shroyer, Historical trends in Ground-based Optical Space Surveillance System Design, AMOS Conference Proceedings, 2007.
2. Jo, J. H. et al, Early CAL/VAL process for an optical tracking system by Korea, AMOS Conference Proceedings, 2015.
3. Park, S. et al, Development of a Data Reduction algorithm for Optical Wide Field Patrol, JASS, Vol. 30, No. 3, 193-206, 2013.
4. Park, M. et al. Minimum Number of Observation Points for LEO Satellite Orbit Estimation by OWL Network, JASS, Vol. 32, No. 4, 357-366, 2015.
5. Milani A. et al. Orbit determination with very short arcs. I admissible regions, Celestial Mechanics and Dynamical Astronomy, Vol. 90, No. 1-2, 57-85, 2004.
6. Kim, Y-R et al., The challenge of precise orbit determination for STSAT-2C using extremely sparse SLR data, Advances in Space Research, Vol. 57, 1159-1176, 2016.
7. Ning Z. et al., Shor-arc batch estimation for GPS-based onboard spacecraft orbit determination, Journal of Global Positioning Systems, Vol. 1, No. 2, 106-112, 2002.
8. Oza, D. H., et al. TDRSS-user orbit determination using batch least-squares and sequential methods. Flight Mechanics Estimation Theory Symposium, 129-144, 1992.
9. Jizhang S. et al., Experimental results of debris orbit predictions using sparse tracking data from Mt. Stromlo, Acta Astronautica, Vol. 102, 258-268, 2014.
10. Bennett J. C. et al. An analysis of very short-arc orbit determination for low-Earth objects using sparse optical and laser tracking data, Vol. 55, 617-629, 2015.
11. Jizhang S. et al., Estimation of ballistic coefficients of low altitude debris objects from historical two line elements, Advances in Space Research, Vol. 52, 117-124, 2013.
12. Genova, A. et al., A batch-sequential filter for the BepiColombo radio science experiment, Journal of Aerospace Engineering, Sciences and Applications, Vol. 4, No. 4, 17-30, 2012.
13. Choi, J. et al, Determining the rotation periods of an inactive LEO satellite and the first Korean space debris on GEO, KOREASAT 1, Vol. 33, No. 2, 127-135, 2016