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Determining the Rotation Periods of an Inactive LEO Satellite and the First Korean Space Debris on GEO, KOREASAT 1

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Inactive space objects are usually rotating and tumbling as a result of internal or external forces. KOREASAT 1 has been inactive since 2005, and its drift trajectory has been monitored with the optical wide-field patrol network (OWL-Net). However, a quantitative analysis of KOREASAT 1 in regard to the attitude evolution has never been performed. Here, two optical tracking systems were used to acquire raw measurements to analyze the rotation period of two inactive satellites. During the optical campaign in 2013, KOREASAT 1 was observed by a 0.6 m class optical telescope operated by the Korea Astronomy and Space Science Institute (KASI). The rotation period of KOREASAT 1 was analyzed with the light curves from the photometry results. The rotation periods of the low Earth orbit (LEO) satellite ASTRO-H after break-up were detected by OWL-Net on April 7, 2016. We analyzed the magnitude variation of each satellite by differential photometry and made comparisons with the star catalog. The illumination effect caused by the phase angle between the Sun and the target satellite was corrected with the system tool kit (STK) and two line element (TLE) technique. Finally, we determined the rotation period of two inactive satellites on LEO and geostationary Earth orbit (GEO) with light curves from the photometry. The main rotation periods were determined to be 5.2 sec for ASTRO-H and 74 sec for KOREASAT 1.

Keywords: KOREASAT 1, ASTRO-H, rotation period, differential photometry, light curve

1. INTRODUCTION

Kessler proposed the possibility that space object collisions could contribute to an exponentially growing number of space objects in low Earth orbit (LEO) back in 1978 (Kessler et al. 2010). Space debris can be created not only through the launch of or collisions of space objects, but also through self-explosions or equipment deterioration (Schildknecht 2007). As of April 20, 2016, among the total 41,448 cataloged space objects, only 1,466 objects could be classified as being in the active state. A total of 34,152 objects have been listed as space debris (Celestrak 2016). For satellites positioned in the geostationary Earth orbit (GEO), the Inter-Agency Debris Committee (IADC) recommends that retired satellite be transferred to a graveyard area to protect other operational GEO satellites (IADC 2014). However, LEO satellites just remain in orbit after the end of their operational periods until reentry to the atmosphere. These inactive space objects should be monitored to check for orbital evolutions and the creation of small sized space debris that could pose collision or explosion hazards.

The space objects orbiting around Earth are affected by various perturbation sources. The harmonic gravitational acceleration of the Earth and 3rd body gravitational acceleration represent types of gravitational perturbations. Additionally, solar radiation pressure and air drag represent

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types of non-gravitational perturbations. The attitude of space objects can also evolve in addition to orbital motions as a result of various perturbations. In the case of active satellites, the attitude and phase angle effect between the Sun and space objects can affect its brightness. For inactive space objects, tumbles may exist when there is no attitude control. The rotation and tumble of space objects can produce variations in the results obtained on the cross-section area with observation sensors like radars and optical telescopes. Moreover, the signal intensity changes in relation to the cross-section area and the albedo. Typically, an artificial satellite's shape is not as 'smooth' as natural space objects. Thus, surface features can be valuable for assessing objects. Several complicated conditions could contribute to aperiodic brightness variations. Also, it may be difficult to distinguish whether variations in data are due to the effects of rotation and tumble or due to the effects of the shape and materials. However, we can analyze the main rotation period and tumbling of specific targets with light curves. This technique can also be useful for analyzing the shape of the target or effects of the perturbations.

The rotation periods of space objects have attracted the interest of amateur astronomers and researchers as early as the first launch of the artificial satellite Sputnik in 1958. The Belgian Working Group for Artificial Satellites (BWGS) developed a database of flash period measurements for artificial space objects, and it is referred to as the Photometric Periods of Artificial Satellites (PPAS) database. This database contains the observation duration and frequency of the rotation for 1,300 objects from 1958 to 1998 (De Pontieu 1997). The data show that the flash rate and frequency of brightness variation can be changed continuously and also discontinuously. However, discontinuity of the brightness variation is usually rare. Papushev et al. (2009) made observations of inactive GEO satellites using a 0.5 m aperture telescope with a photoelectrical photometer. The secular variation of the brightness was confirmed with Saran solar observatory (SSO) observation data from 1995 to 2003 and PPAS data. The Naval Research Laboratory's telescope at the Midway Research Center was used for observations of retired GEO satellites. To extract frequency information, they utilized the Fourier analysis of light curves (FALC) technique and the novel cross-residuals method (Binz et al. 2014). Cognion (2014) measured the variation of the brightness of five satellites within the Geostationary Operational Environmental Satellite system (GOES). Satellites in the GOES constellation were built at the same time and decommissioned sequentially over a 10 yr period. In the case of LEO satellites, the observation conditions are more limited because of the observation durations and geometric conditions. Yanagisawa & Kurosaki (2012) estimated the shape, rotational axis, and rotation period for Cosmos 2082's rocket body with light curves. The rocket body has a long cylindrical shape and uniform surface albedo. Generally, the payloads of inactive satellites have more complicated shapes and material compositions. Hall & Kervin (2014) attempted to detect the synodic variations from ground observation of rocket-bodies. They concluded that shape-dependent spin state analysis methods are needed to overcome the difficulty in detecting synodic variation. Roh et al. (2015) quantified the variations of the brightness of LEO satellites observed by the optical wide-field patrol network (OWL-Net). The phase angle and range effects were corrected. However, some brightness variations caused by the shape and attitude remained.

As the 11th space club member, the Republic of Korea has launched 11 LEO satellites and 7 GEO satellites. Presently, as of April 2016, 9 of these satellites including 6 LEO satellites are inactive. These inactive satellites need to be monitored consistently to assess the orbital information and to check their status in regard to space safety. The Center for Space Situation Awareness (CSSA) at the Korean Astronomy and Space Science Institute (KASI) has been using OWL-Net to track domestic LEO satellites and GEO satellites with five optical observatories equipped with automatic operation systems. The CSSA has a plan to track the entire fleet of Korean satellites including the inactive satellites. We used the OWL-Net observatory in Israel to track ASTRO-H. Additionally, the wide field telescope 3 (WFT-3) was used to collect observations on KOREASAT 1. The WFT-3 is not part of OWL-Net, but it has been used as an auxiliary system during the construction period for the OWL-Net.

We determined the rotation period of the LEO satellite, ASTRO-H, and the GEO satellite, KOREASAT 1. The ASTRO-H satellite was launched on February 17, 2016. On March 26, 2016, the Japan Aerospace Exploration Agency (JAXA) acquired information suggesting that the satellite had broken up. The KOREASAT 1 satellite was decommissioned and deorbited in 2005, and its rotation period was compared with other decommissioned GEO satellites. The rotation period study of satellites can be utilized to 1) check the physical status of target space objects, 2) estimate the shape of un-modeled space objects and 3) analyze the secular variation of the attitude of space objects by perturbations and space weathering. In case of the ASTRO-H, the rotation period determined by JAXA was cross-checked with this study. The rotation period of the early part of this break-up could be good for making comparisons with data collected in later years. KOREASAT 1, space debris on GEO, can be used to analyze long term variation of satellite's attitude change by dynamic perturbations and other reasons. We check the status of first Korean space debris and these data should be useful for understanding the physical changes or orbital variations of inactive space objects with the additional future observation.

2. ROTATION PERIOD OF THE LEO SATELLITE, ASTRO-H

ASTRO-H was a space observatory designed by JAXA for studying the universe with the hard X-ray band. It was originally named as the New X-ray Telescope (NeXT). ASTRO-H was launched on February 17, 2016 (Takahashi 2013). Before the test observation phase planned for June, a critical operation phase, performance verification phase, and calibration phase were set to take place over a period of about 14 weeks. According to the Joint Space Operation Center (JSpOC), ASTRO-H broke up at approximately 01:42 ± 11 min UTC on March 26, 2016. The Bisei Space Center and the University of Tokyo acquired optical observations on March 28 and 31, respectively. The Subaru telescope was also used to check the status of ASTRO-H, and these details are still under investigation. The estimated rotation period was calculated at about 5.22 sec from the light curve results constructed with observation data collected on March 31 with the Kiso wide-field CMOS camera. JAXA has made short-term plans for collecting additional observations via ground-based telescopes and long-term plans for recovery procedures. JAXA announced that function could not be restored to ASTRO-H on April 28, 2016 (JAXA 2016). JSpOC registered 10 objects, numbered from 41,438 to 41,447, as fragments of ASTRO-H. Objects 41,438 and 41,443 were included on the predicted reentry list. These are predicted to reenter the atmosphere sometime until May 10, 2016.

The OWL-Net system in Israel was used to collect test observations of the ASTRO-H satellite. On April 7, 2016, we observed ASTRO-H over a period ranging from 17:56:03 to 17:57:00 UTC. We obtained five images and 135 streak-lets successfully from six shots. The average exposure time was 3.45 sec, and the maximum elevation was 22°. During normal operations, the OWL-Net system calculates the astrometric position of each streak-let with matched time information automatically. However, some of the relevant signals from ASTRO-H were very faint or absent, and thus, we matched the detected streak-lets and time information by hand with the calculated angular rates (Park et al. 2013). The maximum chopper speed was set to 50 Hz, so the minimum exposure duration time was about 0.02 sec. Fig. 1 shows an observation image of ASTRO-H and the detection results. Each streak-lets' magnitude was analyzed with the amount of flux by using Source Extractor software and the matched time tagging duration technique (Bertin & Arnouts 1996). Some streak-lets could not be detected because of the brightness and other unknown reasons. We suspect that ambiguous boundaries of too bright streak-lets and irregularities of the corresponding shapes played a role. Additionally, some streak-lets were too faint to detect properly. We adjusted the brightness scale of each image with the cataloged magnitude. Instrumental magnitudes with R-filter adjustments were converted with 10 comparison stars for each image with the UCAC-4 (U.S. Naval Observatory CCD Astrograph Catalog). The average instrumental magnitude uncertainty was 0.026. And average magnitude uncertainty of comparison stars from the catalog was 0.041. The brightness variation effects due to the phase angle and slant range were insignificant. The phase angle was varied from 89.904 to 89.907°. Additionally, the slant range was decreased to just 70 km from the first point (1,328 km). The brightness magnitude was varied at levels under 0.1.

We analyzed the rotation period of ASTRO-H with the PERIOD04 program (Lenz & Breger 2005). Figs. 2 and 3 show the corrected magnitude variations of ASTRO-H and the fitting results. The light curves of the magnitude variations in Figs. 2 and 3 illustrate the effects of rotating and tumbling. However, here, we only considered the main rotation effects and not the tumbling effects because of the lack of the observation points. There were three high peaks and one small peak within a period of about 2.6 sec. We analyzed the frequency from the peak to peak variation. The determined

Fig. 1. OWL-Net observation image of ASTRO-H detected at 17:56:37.61 UTC on April 7, 2016. The trajectory of ASTRO-H made streak-lets (dashed line) with the chopper system.

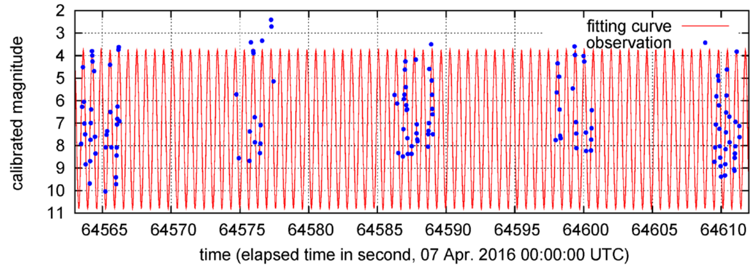

Fig. 2. Whole brightness observation of ASTRO-H and the fitting curve.

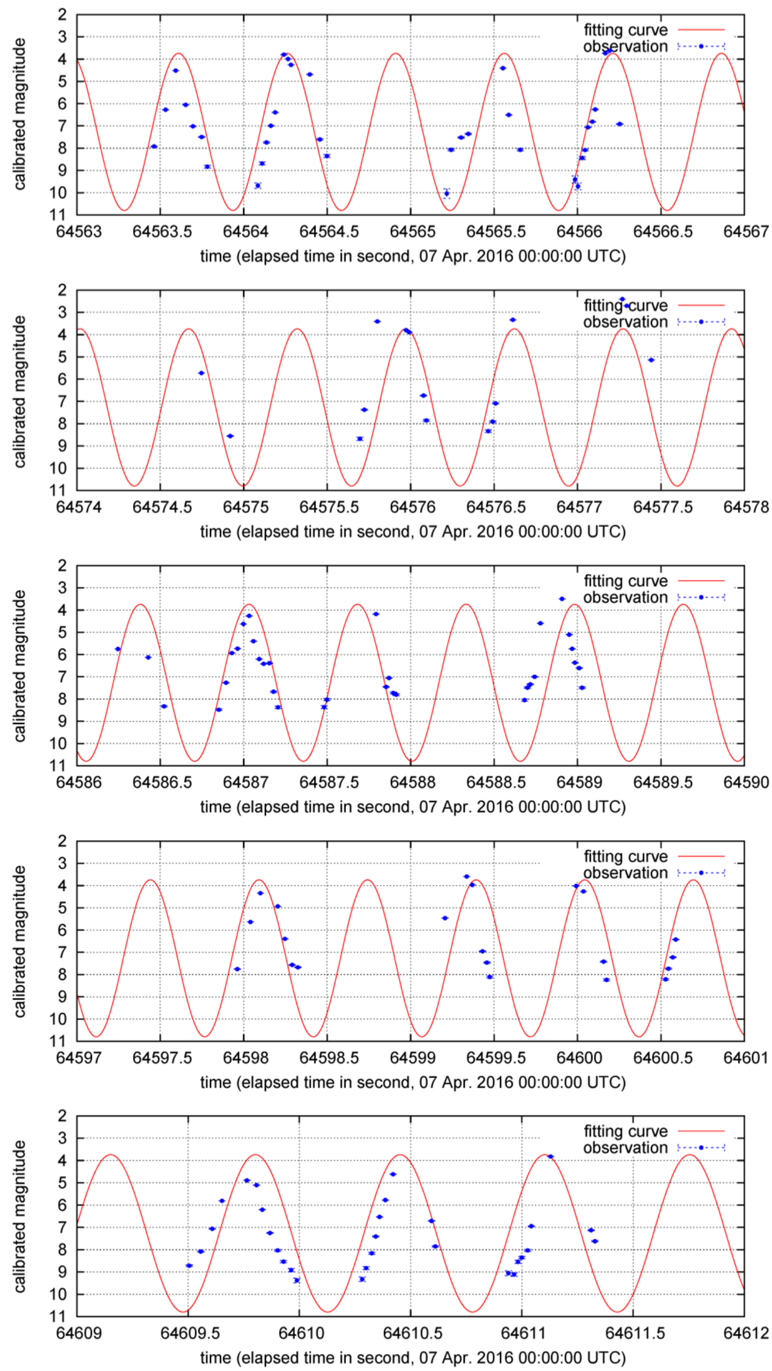

Fig. 3. Whole brightness observation of ASTRO-H and the detailed fitting curve.

frequency was 1.5370 Hz, which corresponded to 0.650 sec. The sigma uncertainty of the determined rotational phase was 0.0141, which corresponded to 0.009 sec. If the front and back side of the object were considered, the rotation period was determined to be about 5.20 sec. Fig. 4 shows the relation between the rotational phase and magnitude variation. The observation near 0.3 phase was absent because of the faint signal. The brightness curve shown in Fig. 4 was widely dispersed over the whole rotational phase angle. It was suspected that time matching errors and small tumbling effects mainly contributed to this effect.

JAXA presented results for the convolution with a period of 5.22 sec on April 8, 2016, and these results were derived from observations taken on March 31, 2016. The OWL-Net system observed ASTRO-H after 7 days from the date of JAXA's observations, and the rotational periods were almost the same. Thus, it could be assumed that there was no catastrophic event involving ASTRO-H during these 7 days. This confirmation of the rotation period of ASTRO-H will be useful for analyzing the long-term rotation period changes and other events.

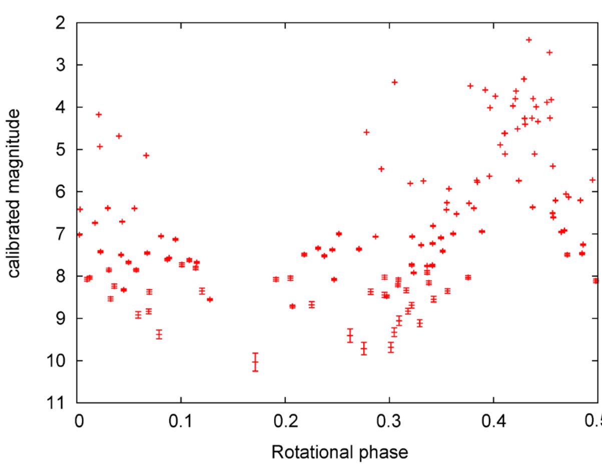

Fig. 4. The rotational phase versus the magnitude with error bars for ASTRO-H. The observation near 0.3 phase was absent because of the faint signal.

3. ROTATION PERIOD OF THE FIRST KOREAN SPACE DEBRIS ON GEO KOREASAT 1

KOREASAT 1 was launched on August 5, 1995, and decommissioned on December 16, 2005. Originally, the planned operational duration was set for 10 yr, but it was reduced to 4 yr and 3 month because of a partial failure at launch time. After its period of inclined orbit operation, KOREASAT 1 was deorbited to the graveyard area 200 km over GEO on December 16, 2005.

The orbital elements of KOREASAT 1 have evolved under the influence of natural perturbations. In natural states, GEO space objects will drift in longitudinal and latitudinal directions. Such drift of space objects can be hazardous to other operational GEO satellites, as decommissioned satellites should deorbit over the GEO region (Choi et al. 2015). Fig. 5 shows the orbital evolution of KOREASAT 1 for the semi-major axis and the inclination. The semi-major axis was extremely elevated after deorbiting took place in 2005. It took about 5.5 month for one cycle of revolution. The inclination particularly increased at the beginning of inclined orbit operation. After that, the inclination changes showed smooth growth tendencies. Naturally, the inclination varied with oscillations under 15°.

We started an optical observation campaign for KOREASAT 1 in 2013. WFT-3 was used for a 2 days observation campaign. The observations were collected from 14:38 to 17:15 UTC on July 23, 2013. The exposure time was set to 2 sec for each observation, and the time span between observations was about 4 sec including read-out time. During this campaign, we obtained 1,588 images successfully. Among the images collected, 859 images were used for the rotation period analysis with consideration given to the others as a comparison set. We used a clear filter for maximum flux. In the case of KOREASAT 1, we could obtain single streaks for each image. So the instrumental brightness of one streak was compared to the others to confirm the overall brightness variation. In these observations, we could not correct the instrumental brightness with the star catalog because of the use of the clear filter.

We used asteroid spin analysis package (ASAP) program to calculate the differential magnitude of KOREASAT 1 (Kim 2014). The WFT-3's field of view (FOV) was 56 arcmin, and

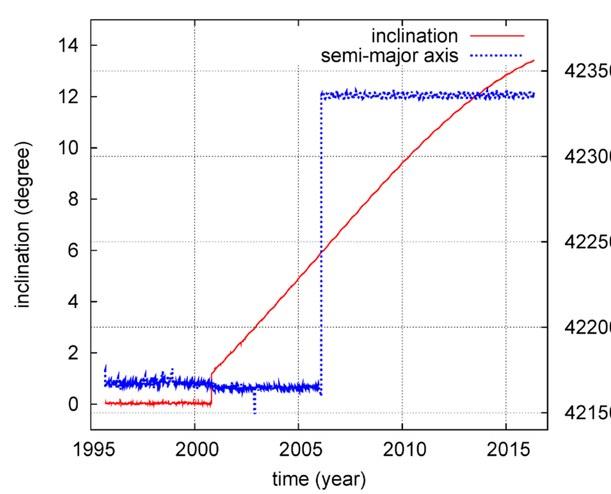

Fig. 5. The orbital evolution of KOREASAT 1.

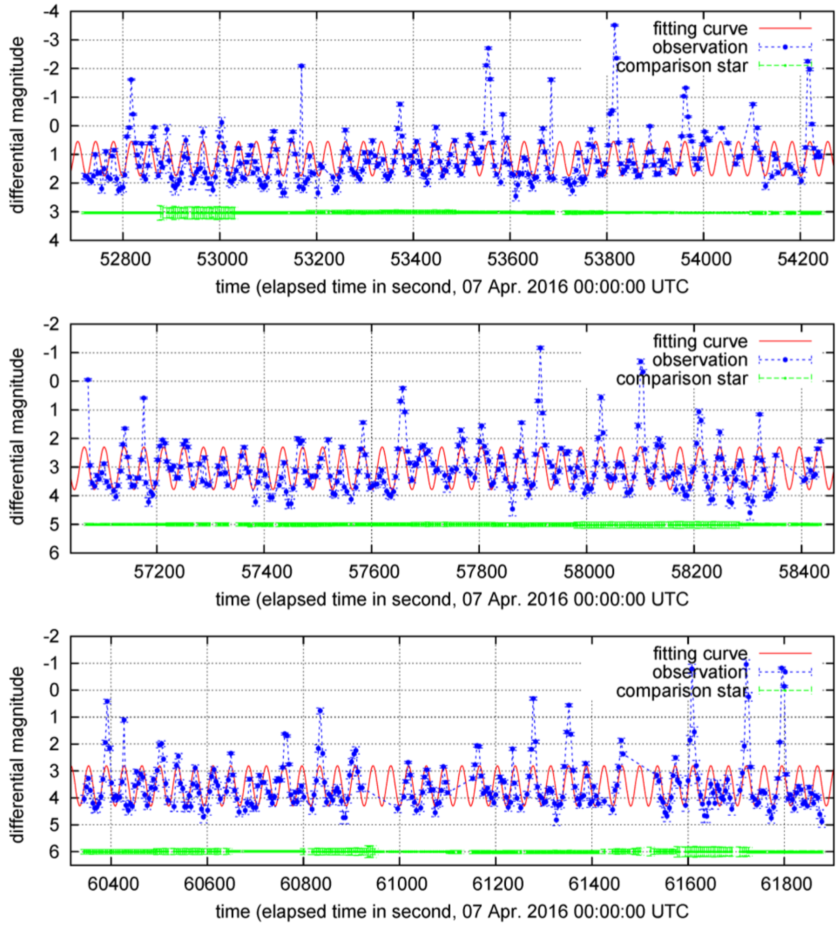

Fig. 6. The brightness variations (point and error bars) of KOREASAT 1 and its fitting curves. Some irregular brightness changes were detected.

the observation time span was 4 sec. We divided the total number of images into 40 sets for differential photometry with comparison stars. Each set included about 30 images, and the maximum angular distance between the first and last images was about 33 min. The ASAP program found the comparison stars and conducted the differential photometry. After the first photometry assessment, we made sub observation sets to match each set's scale. The sub observation sets consisted of the second half of the prior original set and the first half of the next original set. The differential brightness was re-matched to its scale again with the two original sets and one sub-set, and this process was repeated to the last set. However, the total observation sets had to be divided as three pieces because of the lack of observations. The average instrumental magnitude uncertainty was 0.104. And average instrumental magnitude uncertainty was 0.068. We disregarded the ranging effect for the inclined GEO space objects. In regard to the phase angle, it was increased from 2 to 39°. In this case, surface brightness was decreased from 99.9% to 80.9% with the Lambert phase function condition. This phase angle variation could cause a maximum difference of magnitude of 0.28. The fitting amplitude difference between the first set and the last set was 0.22. Thus, it was confirmed that the phase angle variation still affected the brightness variation of KOREASAT 1 in the rotating and tumbling situation.

The rotation period of KOREASAT 1 was analyzed with the PERIOD04 program. Fig. 6 shows the brightness variations obtained with the differential photometry and curve fitting results. Each graph shows the observation data and its error along with the fitting curves and brightness variations of comparison stars. We analyzed the main rotation period and obtained the same results for each case. The determined frequency was 0.0270 Hz, and this corresponded to 74.074 sec with consideration of the front and back sides of the satellite. The sigma uncertainty of the determined frequency was averagely 0.0147 for three sets, which corresponded to 0.547 sec. However, we did not have any in-situ information on the shape, attitude, and material's albedo. The initial shape and attitude state were considerable, but other statuses

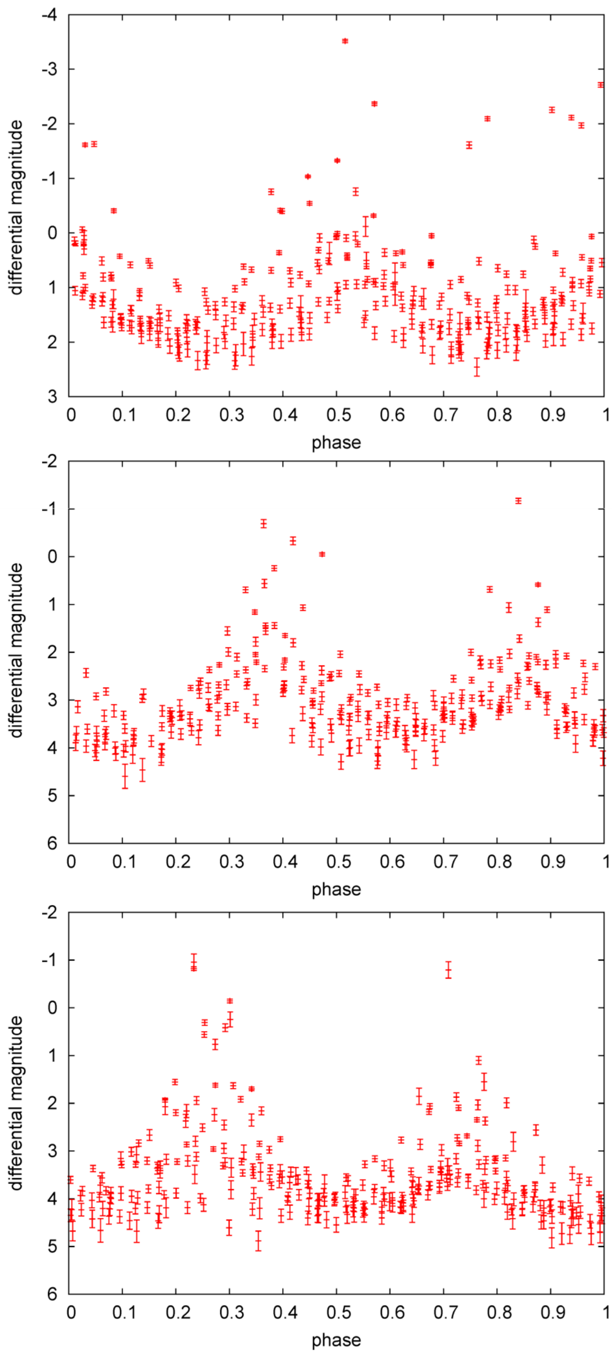

Fig. 7. The rotational phase angle and differential magnitude with error bars for KOREASAT 1.

such as the solar panel angle or rotational pole were still significant factors. These unknown factors and tumbling or precession of poles could have affected the remaining brightness variations. Fig. 7 shows the rotational phase angle and differential magnitude of KOREASAT 1. Every set showed certain patterns with the rotational phase, but there were deviant points from the rotational phase tendency. This was caused by the irregular sparkle points.

The determined rotational periods of KOREASAT 1 were compared with the PPAS data. Although KOREASAT 1 was deorbited after the end of the PPAS data collection period, we could compare it with the other satellites' rotation periods. Papushev et al. (2009) determined the distribution of uncontrolled satellite rotation periods observed in SSO during 1987–2004. Most uncontrolled GEO satellites rotate with a period of 240 sec. There were no significant changes in the rotation period or direction over the long-term duration. The determined rotation period of KOREASAT 1 was within the range of other uncontrolled GEO satellite rotation periods. The effect of external forces like solar radiation pressure and Lorentz force were minor in regard to the change in the rotation period. Thus, an internal process that led to changes in the moment of inertia is thought to be the main cause for the satellite rotation and its variations (Papushev et al. 2009).

4. SUMMARY

We determined the rotation periods of the inactive LEO satellite, ASTRO-H, and the inactive GEO satellite, KOREASAT-1. ASTRO-H was launched on February 17, 2016, and it was presumed to have broken up on March 26, 2016. The observations were made 12 days after the estimated break-up date. The OWL-Net observatory in Israel was mobilized to acquire raw measurements, and 135 streak-lets were acquired from six shots. The determined rotation period was 5.20 sec for the main rotation. This value was almost the same as the observation results reported by the University of Tokyo, i.e., 5.22 sec. KOREASAT 1 was deorbited in 2005. Since then, it has drifted in the graveyard area outside the GEO region for the last 10 yr. We conducted an observation campaign for KOREASAT 1 by using the WFT-3 system for 2 days. The main rotation period was determined to be about 74.074 sec. Even though there were some irregular peaks, the main rotation period was maintained for 2.5 hr. This rotation period was acceptable in comparison with other inactive GEO satellites' rotation periods in the PPAS data set.

In the case of the inactive LEO satellite, a fast sampling period and big aperture were required to obtain the proper time resolution and to produce an acceptable signal to noise ratio. In general, LEO satellites have relatively short observation windows compared to GEO satellites. The OWL-Net system has the capacity to resolve fast rotation periods of LEO satellites or natural bodies with the chopper system. Because of the unclear cause of the break-up of ASTRO-H, early observations were important for the assessment of rotation period changes if any, and to explore the likelihood of an explosion and collision. Our observation results agree with the analysis by the University of Tokyo. We concluded that there were no additional physical change of the ASTRO-H after the observation by the University of Tokyo. The physical status of the ASTRO-H was not presented after the event. The brightness variation study also can be used to estimate the shapes of main part of the ASTRO-H.

The rotation period of KOREASAT 1 was determined to be within a comparable range to the PPAS data set. KOREASAT 1 was first Korean space debris on GEO. It is needed to monitor the domestic space debris continuously for the safe usage of the space. We only analyzed the main rotation period in this work. We also found that there were other irregular brightness changes and these brightness variations were larger than main brightness variations. We speculate that this was caused by solar panel reflections or other tumbling effects. This results can be used to confirm the long-term variation of the rotation period with additional observation by the OWL-Net. It is required that yearly observation to analyze the secular change by various reasons like Yarkocsky-O'Keefe-Radzievskii-Paddack (YORP) effect (Albuja et al. 2015).

It was difficult to determine the attitude of inactive satellites without in-situ information exactly. However, both inactive satellites showed specific main rotation periods with some tumbling effects.

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