Geostationary Earth Orbit Region Survey with The Optical Tracking Network, OWL-Net

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ABSTRACT

As the number of space objects grows, Geostationary Earth Orbit (GEO) satellites are also threatened by space debris and uncontrolled space objects. Collisions with other GEO space objects and fragmentation in orbit are the main hazards for GEO satellites. To date, 11 GEO satellites have been launched as Korean space assets. Sometimes, collision threats with Geosynchronous Orbit (GSO) satellites like Raduga or telecommunication errors caused by eclipsing by other space objects occur. The Optical Wide-field patrol-Network (OWL-Net) was developed to track Low Earth Orbit satellites and monitor the GEO region for Space Surveillance Awareness. Five stations, located in Mongolia, Morocco, Israel, the United States, and South Korea, have been installed, and the OWL-Net can provide global monitoring for the GEO region with those robotic telescopes. The OWL-Net can achieve mosaic screens in latitudinal and longitudinal directions with the GEO and GSO monitoring observation mode. The astrometric and photometric data can be produced as monitoring results for the detected space objects. The astrometric measurements in time series are compared with the publicly released orbital data TLE (Two-Line Element sets) for confirming the orbital keeping maneuver and detecting unidentified objects. In this presentation, the operation results for GEO monitoring test results are shown.

1. Introduction

The threat posed by space objects is continuously increasing. The threat from collisions of space objects is mainly growing in the low Earth orbit (LEO) region. Small satellites including CubeSats, mega constellations like Starlink, and increased space activities are the primary causes. As of August 2023, there are approximately 57,700 registered space objects. Among them, there are around 27,800 space objects currently in orbit, and approximately 29,900 space objects that have decayed. Furthermore, it is known that there are about 8,600 operational space objects. On the other hand, the collision threat between space objects in the geostationary orbit is also continuously rising. The geostationary Earth orbit (GEO) is a limited area with an altitude of 35,786 km from the Earth's surface, shaped like a belt, compared to the LEO. Accordingly, the GEO is divided into zones for the placement of satellites and is managed. Recently, multiple GEI satellites are sometimes redundantly placed within a single area. The main causes of collision risks for GEO space objects are drifting of the GEO satellite to other GEO satellite located area and fragmentation in satellite orbits.

To mitigate the risk of collisions between space objects, it's important to ascertain the orbital information of both the primary object and the secondary object. Collision information for objects in danger of colliding and the potential collision target can be checked through sources like space-track, Celestrak's SOCRATES, and others. This information includes details such as Time of close-approach, minimum range, and collision probability between space objects. Collision analysis involves utilizing orbital information from operators and observational data. Operational space objects are those for which the operator possesses orbital information. However, since orbital information for both objects involved is necessary, obtaining orbital information for non-operational space objects requires observational data about those objects.

There are various observation equipment used to monitor space objects. The main observation equipment includes optical system, radar system, and laser system. Radar systems are minimally affected by weather conditions and can receive transmitted signals, allowing them to operate without significant limitations on observation time. Additionally, phased array radars can track multiple space objects simultaneously. However, the required transmitted energy

depends on the range between the space object and the radar system. Therefore, radar systems are not suitable for monitoring space objects that are relatively far away, such as those in GEO orbits. Laser systems can precisely measure the range to space objects. However, the limited beam width of lasers makes them inappropriate for use as surveillance systems. The optical systems are significantly affected by weather conditions. Additionally, space objects need to reflect sunlight for observation. Nevertheless, optical systems have fewer distance-related constraints as the optical system don't transmit signals. Furthermore, optical systems are relatively cost-effective. Therefore, optical systems are primarily used for monitoring space objects in GEO.
In 2011, there was a collision risk between the Raduga 1-7 satellite and South Korea's GEO satellite COMS-1[1]. In 2017, ExoAnalytic Solutions captured the explosion of the Telkom-1 satellite[2]. Additionally, South Korea is developing its own satellite navigation system through the KPS project. The KPS satellites cover not only GEO but also include Geosynchronous orbit satellites with larger orbital inclinations[3].
The Optical Wide-field patroL-Network (OWL-Net) is a space surveillance optical tracking network system developed in South Korea, with its development completed in 2016. OWL-Net is primarily designed for tracking domestic LEO satellites and monitoring GEO region. Its primary mirror has a diameter of 0.5 meters and is mounted on a robotic mount. OWL-Net operates as an unmanned automated observation facility, utilizing weather check equipment to autonomously determine observation feasibility. The observation schedule is automatically generated based on user-inputted observation target list at the headquarters in South Korea and then transmitted to the local observation site. The operational system at the site makes the final decision for observation based on weather conditions and equipment health status to perform the actual observations. Observation targets can encompass not only space objects but also specific designated regions. The designated regions are typically specified using latitude, longitude, and zenith altitude information.
Furthermore, OWL-Net employs various observation modes, which can also be distinguished based on whether the observation target is a space object or a specific region. For tracking LEO objects, an observation mode that utilizes rapid tracking and exposure times on the order of 50Hz using a chopper is employed to obtain a large number of observation points. On the other hand, for monitoring the GEO region, users can specify specific exposure times that match the orbital motion of GEO satellites and consider telescope movement based on the distribution of GEO space objects.
In this study, the test results of OWL-Net's GEO region survey observations for monitoring GEO objects are presented. Primarily, observations were conducted in the GEO region, which refers to the GEO belt. The detected results of space objects were compared to publicly available space object orbital information, Two-Line Element (TLE) data, for identification. From the identification results, various sources of errors were confirmed. Through this, we conclude the feasibility and necessity of independent geostationary orbit area monitoring.

2. OWL-Net high-altitude objects survey

OWL-Net's five observation sites are strategically positioned along longitudes to ensure comprehensive coverage for observing both LEO satellites and monitoring the GEO area. These sites are located in Mongolia, Morocco, Israel, the United States, and South Korea. Fig. 1 displays the positions and names of each observation site, along with the scenic views of the sites. For automated observations, the observation sites require electricity and communication facilities. Due to the significance of observation conditions, they are primarily established around existing astronomical observatories.

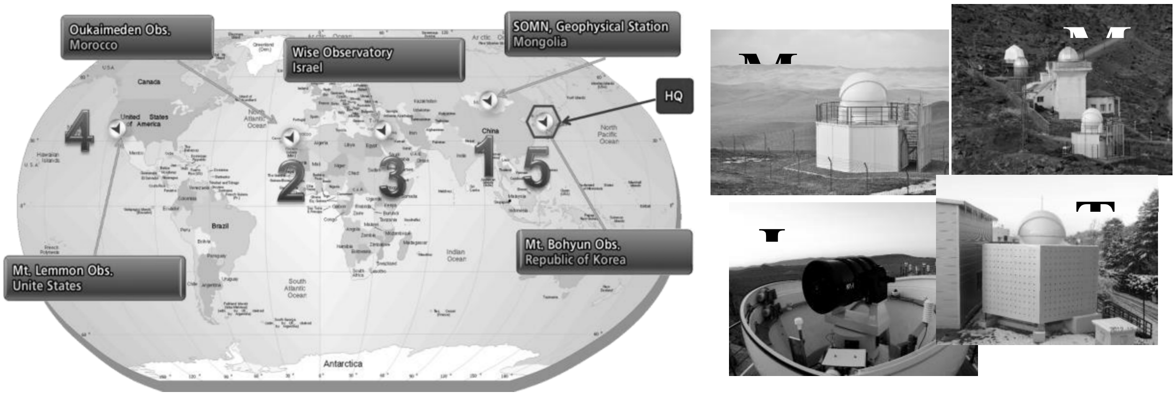

Fig. 1 Optical Wide-field patrol-Network (OWL-Net) site location and scenic view of four sites.

OWL-Net was initially developed with the primary goal of tracking national space assets. For LEO objects, it tracks and observes secondary space objects that are potential collision candidates. Utilizing the acquired observation data, it can be utilized to estimate orbital information, which is then used to analyze collision risks for primary objects. On the other hand, collisions among GEO objects are mainly caused by the relative motion of space objects in the same GEO. GEO objects periodically perform station-keeping maneuvers to ensure they remain within their designated areas. Without these maneuvers, GEO objects would drift. Drifting GEO objects move around the stable points in the Indian and Pacific Oceans, crossing the GEO. According to a study by Oltrogee[4] in 2018, among around 34,000 Conjunction Data Messages (CDM) for GEO objects between 2014 and 2017, 55% of collision risks were from collisions between operational GEO satellites, followed by GEO-proximity debris. This would likely encompass a significant portion of risks involving co-located GEO objects. However, drifting GEO objects approach other objects of interest over the span of days or weeks. Therefore, regularly surveying the GEO area to verify whether GEO objects remain on their known orbits, and to identify any drifting or unknown space objects, becomes a monitoring task to prevent collisions among geostationary orbit objects.

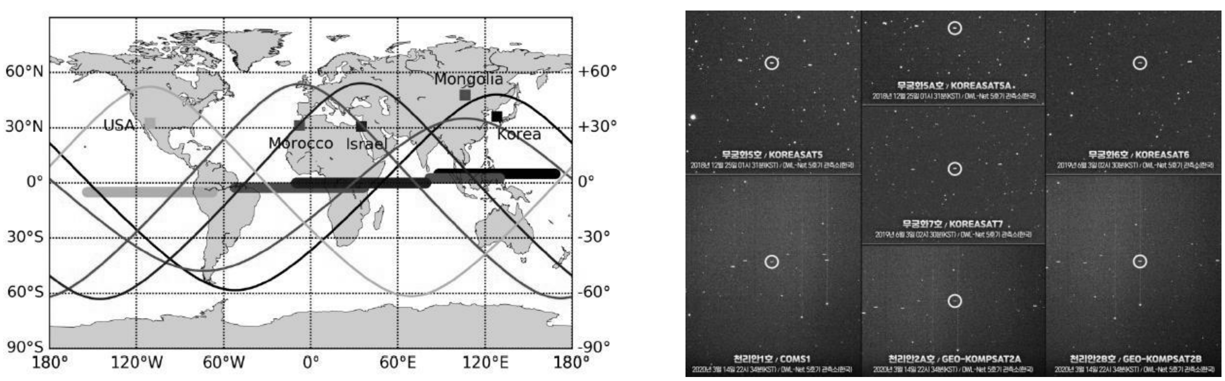

Fig. 2 OWL-Net GEO coverage and elevation for each site and observed image of Korean GEO satellites. [5]

The region where GEO objects exist can be defined in various ways. We adopted the definition of the GEO region used by space-track. In this context, the definition of the GEO is as follows: Mean Motion should be between 0.99 and 1.01, and the orbit eccentricity should be less than 0.01. This definition is related to the shape of the orbit. The inclination of the orbital plane or the ascending node can have various values. The inclination of GEO objects naturally increases up to around 15 degrees and then decreases, and this variation repeats. Changes in the orbital inclination can also become a variable in assessing the collision risks of space objects.

3. Survey observation data reduction and test result

As mentioned earlier, within OWL-Net, a dedicated observation mode can be generated for observing the GEO region. In this mode, the position of the observation area can be defined using latitude, longitude, and altitude values. The designated location serves as the center for defining the entire observation area in a matrix format. Furthermore, a margin for the observation images can be set.
OWL-Net's field of view (FOV) is approximately 1.1 degrees by 1.1 degrees. The sensor utilizes a CCD with a 4096 x 4096 array, resulting in a pixel scale of about 1 arcsecond. When performing sidereal tracking on GEO objects, they move at a rate of around 15 arcseconds per second. Assuming a seeing of more than 5 arcseconds, an exposure time of at least 1 second is required to detect space objects as streaks.
Observations of the GEO region are conducted in a manner of swiftly surveying a wide area rather than repeatedly observing the same region. Therefore, performing observations using an approach of overlapping images to detect moving objects is challenging. Even if such observations were attempted, the angular velocity of GEO objects is relatively slow compared to LEO objects, requiring sufficient time intervals to detect these objects. Thus, a method that secures a sufficiently long exposure time to detect space objects was preferred.
On the other hand, non-sidereal tracking that matches the speed of space objects can be employed to observe faint space objects like space debris. Since GEO objects are nearly stationary in the view of ground-based observer, methods involving exposing without moving the mount could also be used. However, in the presence of numerous stars, stars could produce streaks that might cover GEO objects. Therefore, for this experiment, sidereal tracking was chosen.
For the purpose of GEO survey, a matrix of 99 x 1 was established for testing. The margin for the observation images was set at 30%. The exposure time was set to 2 seconds. Testing was conducted using the OWL-Net system in the United States, with observations configured to be centered around the geostationary orbit position in the southern direction.
When conducting GEO observations, the criteria for dividing the matrix are as follows. While considering existing methods based on right ascension and declination or altitude and azimuth, it was recognized that GEO objects move in terms of latitude and longitude, i.e., within the Earth-Centered, Earth-Fixed frame. Thus, specifying the observation area based on latitude and longitude reduces potential errors that users might have in using topocentric coordinates as shown in Fig. 3. Additionally, this approach is relevant when observing space objects with a high orbital inclination. GEO objects with a high orbital inclination, while exhibiting an 8-shaped trajectory, tend to move almost entirely along the same longitude. Observing while maintaining the same longitude is convenient for analyzing collision risks among space objects within that region. The margin of the observation image is also designed to yield appropriate results from various azimuth angles, considering ground-based observers as reference points. Furthermore, observations are prioritized along the same longitude, i.e., vertically. Unlike methods such as spiral surveys used in existing galaxy surveys, this approach is not attempted, as GEO objects with high orbital inclinations move in a vertical manner relative to the orbital plane, vibrating once per day. Therefore, performing observations based on the same longitude allows for easier detection of GEO objects passing through the same area at the same time.
We can perform repeated observations of this matrix. The time required for a single observation of the GEO region from a single observation site is generally less than 20 minutes. Therefore, depending on the objective, we can observe the GEO region multiple times throughout the night or carry out different types of observations. If the goal is to observe co-located space objects, it's possible to focus on observing a single area. GEO objects are usually observable throughout the night, and observations can be extended to satellites from other countries as well, in addition to safeguarding national satellites.

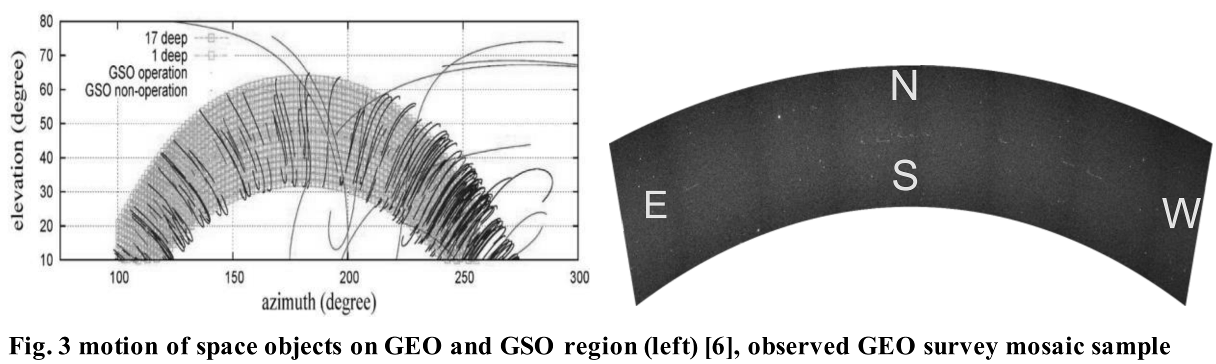

Fig. 3 motion of space objects on GEO and GSO region (left) [6], observed GEO survey mosaic sample image using OWL-Net (right)

The observed images can be combined into mosaic images. Since OWL-Net is located in the Northern Hemisphere, when combining observation images based on Northern Hemisphere observers, the resulting image would appear as shown on the right in Fig. 3. However, this image is a combining of only 8 images. When combining all 99 observation images, a composite image with a thin, elongated belt-like structure similar to the light blue band in the left image of Fig. 3 could be obtained.

Before the mosaic combine of observation images, the process of identifying space objects in each image can be outlined as follows: 1) Remove bias from each image as part of preprocessing. 2) Detect space objects that appear as streaks in the observation images. The detection of space objects was performed using the Source Extractor program. For detection, parameters such as eccentricity, length of the streak's major axis, and the detected minimum area were considered. 3) Download Two-Line Element (TLE) data related to GEO objects from Space-Track on that day. Utilize the TLE data to generate right ascension and declination coordinates of geostationary orbit objects within a FOV 1.5 times the size of the image at the observation time. 4) Compare the detected coordinates of space objects with the calculated coordinates of GEO objects. This process ensures that space objects within the GEO region are accurately identified in the observation images.

Another consideration when combining observation images is the quality of the images. When combining images, there can be cases where the background sky is either dark or bright. If the background sky is bright due to the presence of the Moon or light pollution, simply overlaying images could result in some areas not exhibiting sufficient quality. Therefore, during image combine process, we adjusted the brightness scale of the composite image by comparing it with the left and right images. As a result, the brightness scale adjustment enabled us to maintain the ability to identify observed space objects in the composite image at a level similar to that of individual images.

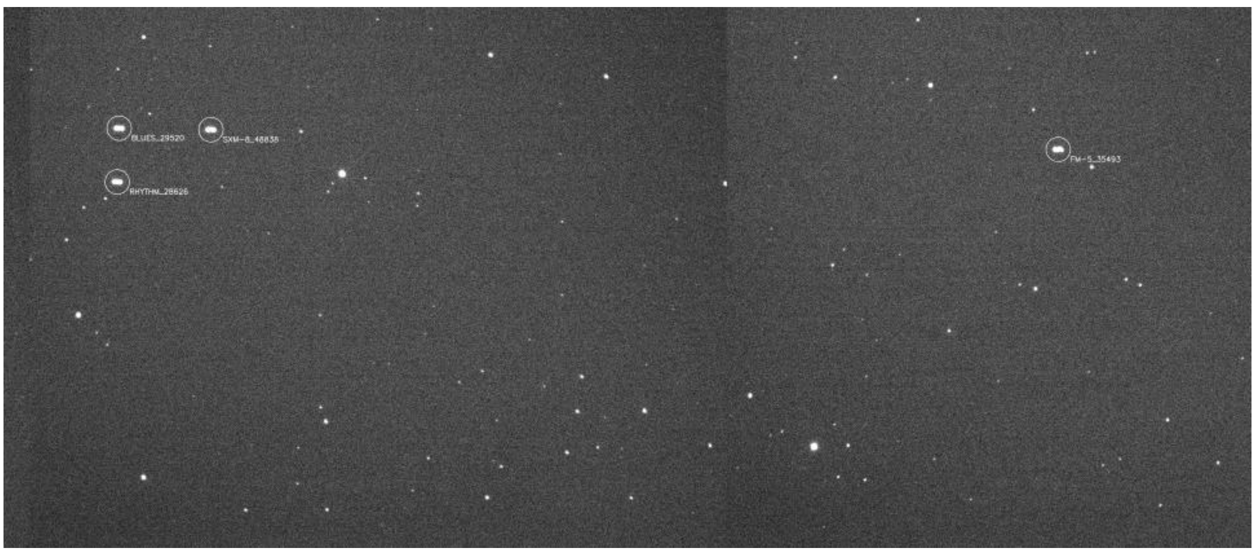

Fig. 4 identification result of GEO object in sample combined image. Co-located satellites are also identified.

Fig. 4 is an example of space object identification. Four space objects were detected in a range of about 1.5 degrees. Of these, three space objects appear to be co-located. The difference in longitude is about 0.1 degrees. When combining the image, the name and CAT ID of the identified space object were written.

Generally, the brightness of GEO satellites changes every night. This is the difference between the phase angle of the Sun, Earth, and satellites. Therefore, the satellite located in the direction of south is the brightest at midnight when it receives and reflects sunlight directly. However, space objects located at the east or west end may be brightest at dusk or dawn, rather than at midnight. The brightness change of the space object according to this observation time also affects the detection rate. Depending on the size of the GEO object, it may not be detected at a specific observation time. Therefore, it is more appropriate to conduct survey observations in the GEO region at various times. The next cause affecting the detection rate is station keeping maneuver in space objects. Station keeping maneuver moves mainly in the east - west direction or in the south - north direction, so errors may occur in detection. However, since the secondary object with a high risk of collision does not mainly perform sta tion keeping manager, the error in detection rate may be reduced compared to the primary object.

Fig. 5 identification result of GEO object in sample combined image. IGSO like object detected (left-up)

In another identification example, a target that appears to be an Inclined GSO space object was detected. However, the TLE we used could not identify the corresponding space object. In addition, there is a space object that has been detected but is not identified on the right side of the lower part of the GEO object belt. The space object was moving at almost the same angular velocity, although it was very faint compared to other GEO satellites. These two unknown space object detection results can be attributed to errors in TLE or errors in the detection process. Another reason may be that this is space objects whose actual TLE information has not been disclosed.

Unknown space objects are of importance as a result of GEO survey. Unknown space objects must obtain orbital information through tracking. In addition, since TLE is not provided, it is necessary to decide whether to be a maneuver on its own. In addition, if an unknown space object drifts in the direction of the space object of our interest, it will track that space object in some period. Meanwhile, detection of faint space objects can be improved by improving the power of the optical system. The main diameter of the OWL-Net is 0.5 meters. Among the telescopes mobilized to track GEO objects in recent years, there are also a number of 0.4 meter-sized telescopes. Each method of increasing observation efficiency by deploying a large number of these small telescopes or increasing the detection rate of a single image using a large telescope with high power has advantages and disadvantages.

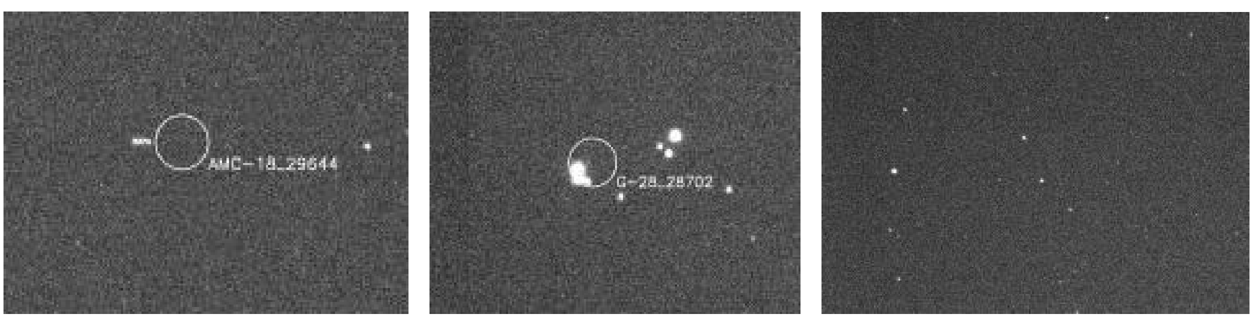

Fig. 6 false identification samples. Maneuver, overlapped with others, too faint to detection.

We analyzed three main causes of failure to identify GEO objects. 1) The satellite may be detected at a position different from the previous predicted position using TLE by the maneuver of the GEO object. 2) Identification fails when bright stars, other objects, LEO satellites, or image errors overlap with GEO objects streak. This case may appear differently from season to season. This usually occurs when there are large amounts of stars in the background. Especially when passing through the Milky Way, it becomes difficult to detect cosmic objects themselves. Therefore, it may be necessary to consider various observation occasion depending on the season. 3) Identification of objects that are too faint can fail because they are not detected. This can be overcome by increasing the power of telescope system as mentioned above. Another cause is a system error. This includes the presence of a space object at the edge of the image. Detection may be difficult at the edge of the image.

Analysis of the test images allowed us to identify 53 Resident Space objects in a single GEO region survey observation. Seven unknown space objects were also detected. A total of 99 observation images were used in the test. Through this, it was possible to cover 90 degrees in the direction of longitude. The longitude of the center of the observation area is -118 degrees.

4. Summary

The optical systems can be mainly used to monitor the collision risk of GEO objects. OWL-Net is the optical observation network consisting of five automatic observation systems worldwide. OWL-Net was developed for tracking domestic LEO objects and monitoring of GEO region. The diameter of the main mirror of the OWL-Net is 0.5 meters. OWL-Net is evenly distributed in the longitude zone. Therefore, almost all GEO region can be observed, not only in Korea.

GEO region survey test observations were performed at U.S. sites. A single observation was performed, and 99*1 images were acquired in the longitude direction. The center of observation is -118 degrees longitude. The FOV of OWL-Net is approximately 1.1 degrees * 1.1 degrees. We set the margin of overlapping observation images to about 30%. Accordingly, the area covered by the observation on the actual longitude was about 90 degrees. The observation took approximately 20 minutes.

A total of 53 space objects were identified and seven unknown space objects were detected as a result of GEO object identification. The reasons that affected the identification of space objects were the positioning maneuvers of space objects, the overlap of space objects with other objects like stars, asteroid, and the case that they were too faint to detect. In addition, System errors also cause space object identification failures. The unknown space object appears to be due to the absence of a space object in the list of GEO TLE used for identification. The unknown object is not a real space object but system error, or a real unknown GEO object.

We would like to develop a dedicated GEO surveillance optical system to monitor the GEO region of Korea and reduce the risk of collision of Korean navigation satellites. To this end, telescopes with a larger main mirror than OWL-Net, new sensors such as CMOS, and newly developed optical systems according to their purpose can be applied. Through this system, it will be possible to secure the capability to protect Korea's GEO space assets.

5. REFERENCES

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