Investigation of a Ground-based Optical Observation System for LEO Objects

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We have examined the possibilities of a ground-based optical observation system for monitoring LEO objects. Simulations and a test observation showed that two longitudinally separate observation sites with arrays of optical sensors can detect many LEO objects 30 cm in size and precisely determine their orbit. The proposed optical survey system may complement or replace the current radar observation system for LEO objects monitoring in the near future.

Keywords: LEO Debris, Optical Observation, Orbit Determination

1. Introduction

The space environment has recently deteriorated due to space debris, particularly in the low-Earth orbit (LEO) region. In order to protect active satellites in LEO, space debris must be precisely monitored. In this paper, monitor means detection of objects, determination of their orbits and maintaining them. Although currently, this is mainly handled by the Space Surveillance Network (SSN), via global radar observation sites of the United States, the SSN detection limit is about 10 cm which is insufficient to protect active satellites. Most satellites cannot survive a collision with an object of 1 cm.

Conversely, optical sensors are mainly used to monitor geostationary (GEO) orbits because GEO is too far for radar observation. However, by enhancing the detection efficiency of optical sensors and PC performance the extremely low cost of optical sensor compared to radar systems may enable them to monitor LEO objects like radars.

Besides, from the optical survey using the NASA 3.0 m diameter Liquid Mirror Telescope, a quarter of LEO objects exceeding 30 cm and a half of those exceeding 10 cm are uncatalogued which means the amount of uncatalogued objects exceeding 10 cm is almost equivalent to the catalogued total. This situation is quite serious and may be attributable to differences between the radar and the optical reflection properties of LEO objects. To complement or replace radars, optical sensors can monitor LEO objects and also have the advantage of being able to determine the positions of space objects to accuracy of within one arc second, which will facilitate precise orbit determination.

In this work, a new LEO monitoring system, which uses an array of numerous optical sensors to detect uncatalogued LEO objects, determine their orbits and maintain them, is proposed. The system will carry out the task which is currently done by SSN. In order to maintain the orbits of uncatalogued LEO objects, the system needs to re-detect the objects the next day within an accuracy of several degrees, which is a typical field...
of view of optical sensors. Although the optical observation with the proposed system is limited by daylight and weather conditions, they are much cheaper than radar systems, which easily outweighs their disadvantage. We carried out some simulations to evaluate the optical system, which showed that identical objects were recognized from the data of four individual sets of equipment installed on two separate sites using the orbital elements of each object. This enables us to determine the orbits of uncatalogued LEO objects precisely. We also carried out a test observation to determine the orbit using actual observation data. The results showed that the optical system is capable of determining the orbits of LEO objects accurately enough to track them the following day using data from two separate sites.

2. Optical Observation System for LEO Debris

2.1. Observation equipment

The optical observation system for LEO debris comprises observation units and data analysis software. Fig. 1 shows the unit which comprises a Canon 200 mm F2 camera lens and a 2K2K back-illuminated type CCD camera ML4240 manufactured by FLI. The field of view (FOV) is 7.65×7.65 -degree.

The transit times across the FOV of the objects at altitudes of 250, 500, 1000 and 2000 km are 4.3-, 8.8-, 18.5- and 39.5-sec, respectively; assuming the unit is observing the zenith. As the readout time of the CCD camera is 1.5-sec, the

zenith pointed unit can observe 12 and 26 times for objects at 1000 and 2000 km, respectively.

2.2. Data analysis software

We developed a line-identifying technique for data analysis8), which is illustrated in Fig. 2 and uses multiple CCD frames. First, it detects candidate objects (the black dots in Fig. 2) as follows. Objects, including fixed stars on the CCD frames, are shown as a gradient feature with a central peak value as shown in Fig. 3. The shape parameter is defined as the sum of the values of the nine pixels in Fig. 3 divided by the central value. Shape parameter values close to “1” indicate that the central pixel has an extremely high value and may constitute noise, while high values of the shape parameter represent signals from objects, as shown in Fig. 3. Candidate objects are searched from the CCD frames using a proper threshold, the proper shape parameter, and the condition that the values of the eight surrounding pixels be less than that of the center. When the threshold is reduced and/or the shape parameter is near “1”, the number of candidates increases, which means many noise pixels are counted as candidates. The method used to determine the number of candidates is explained later. The candidates for every frame are detected using these processes.

After candidates are detected, the technique finds any series of objects arrayed on a straight line in the 3-dimensional space shown in Fig. 2. The x-, y- and z-axes of the 3-dimensional space are defined as the x- and y-coordinates of the CCD frames and the frame number, respectively. Straight lines are detected as follows. First, two frames are selected and the two candidates belonging to each of the frames are marked. Subsequently, the straight line which traverses the two candidates is described in the 3-dimensional space and candidates around the line within a few pixels of the other frames are searched. If the number of searched candidates exceeds a proper threshold, the technique determines that one object is moving across the FOV at constant velocity. These processes are repeated for every two candidates on every pair
of frames.

Using this technique enables us to detect unknown space objects and near-Earth asteroids moving unpredictably. The time required for analysis depends on the number of candidates. For example, a commercial desktop PC (Dell Precision 450) can analyze 18 frames with 400 candidates in each frame in 7 minutes. Using 10 sets of this PC, 14400 frames which are taken within 6 hours’ observation (3 hours for after dusk and 3 hours for before dawn) are analyzed within 10 hours. The proposed system should finish the analysis within 12 hours since detected and orbit-determined objects with the analysis need to be re-observed next day to maintain their orbits. The user can select an appropriate number of candidates per frame and the number of frames by considering the capability of the computer to meet this demand. With sufficient computing power, the number of candidates can be increased by lowering the detection threshold, meaning that darker objects will be detectable.

Since 400 candidates are selected in each frame, most are noise attributable to the fluctuation in the sky background on the CCD sensor, with values above 3.3 times the standard deviation of the sky background value. The technique requires a minimum of 11 candidates to be detected as points of the above-mentioned straight line. The probability of false detection, which would involve 11 incidents of noise of 3.3 sigma of the sky background being coincidentally aligned, is 10 to the power of −34 and thus negligible.

Analyzing the data taken by the unit described in Sec. 2.1 with the line-identifying technique, objects of 30 cm in size at 1000 km altitude are detectable. As described in Sec. 1, a quarter of LEO objects exceeding 30 cm may be uncatalogued. Despite the lack of observation days, a survey using the unit showed that about 15% of detected objects are uncatalogued, which is consistent with the NASA result to some extent. Establishing an optical observation system using an array of the units will contribute to monitor LEO objects which are not currently detectable by radar. To explore more powerful system, we are trying to allow objects of less than 10 cm in size to be detected by modifying observational equipment and data analysis software in the near future.

3. Observation Network

Given the narrow FOV of the observation unit (7.65×7.65 degree), detecting and determining the orbit of numerous LEO objects is difficult with one unit and the use of many units is considered. The main objective of this system is to accurately determine the orbit of uncatalogued LEO objects. A previous study showed observations of two consecutive passes performed at two longitudinally separate sites, whereby two 60 degree separate observations at each site allowed us to determine the orbit precisely9). To meet this demand, we considered the observation network as shown in Figs. 4 and 5. Fig. 4 illustrates the array of observation units at one site. Many units are used to observe two narrow rectangular regions set in an east-west direction. Fig. 5 illustrates two consecutive passes of the same object, which are observed at two longitudinally separate sites. This network can observe many LEO objects four times (2 times per site).

To determine the orbits of detected objects precisely using the network, it is important to be able to identify the same object from bulk observation data taken in by the network. In Sec. 4, the potential for identification was investigated, which was extracting four sets of data on the same object from bulk observation data taken at two sites using simulated data created by STK software10).

4. Observation Simulation

First, two observation sites are chosen. Many LEO objects reside at an altitude of 800-1000 km with an orbital period of about 100 minutes. To observe the same object, which is observed at the first site, in almost the same direction at the second site, the two sites should be separated by about 25 degrees of longitude which is equivalent to 100 minutes of Earth motion. This time, Rikubetsu of Hokkaido prefecture (lat. 43.4565°N, long. 143.7660°E, alt. 363 m) and Ishigaki of Okinawa prefecture (lat. 24.3745°N, long. 124.1390°E, alt. 179 m) were selected as the observation sites.

As shown in Figs. 5 and 6, 40 units of 3.5×3.5 degree FOVs were prepared for each site. This simulation is supposed to use 18 cm telescopes, which is why the FOV of the units is 3.5×3.5 degree instead of 7.65×7.65 degree. Using a 18 cm telescope to improve the signal-to-noise ratio from LEO objects is our future plan. The set of 20 units comprises the FOV in a 70 degree east-west direction and 3.5 degree north-south direction and directed toward the azimuth (Az) 0 degree and elevation (El) 50 degree. Another set of 20 units composes the same FOV and is directed toward Az 180 degree and El 50 degree.

The observation period for Rikubetsu was from 8:40 to 11:40 (UT) on April 11, 2012, while that for Ishigaki was...
from 10:20-13:20 (UT) the same day, namely 100 minutes later than that of Rikubetsu. 14574 two-line-elements (TLEs: orbital elements of catalogued objects) opened to the public by Space Track[12] on April 11, 2012 were used. STK software calculated the observation coordinates (right ascension (RA) and declination (Dec)) of each object per site and per second using these TLEs. Positional errors of up to 0.005 degrees, namely three times the resolution of the equipment, were considered. During the actual observation, we were unaware of the ID of the observed objects and only obtained numerous sets of times and coordinates, meaning identification of the same objects from data of the two sets for each site would dictate whether or not this system is useful.

4.1. Identification of the same objects at each site

Each site has two sets of observation units. At Ishigaki, the first set directed at Az 0 degree and El 50 degree detected 872 objects during 3 hours of observation, while the second set detected 636 objects. 473 objects were detected at both sites. Circular orbital elements were also calculated from the data of each set. The identification conditions were investigated by comparing the observation time and the circular orbital elements. Consequently, the following 5 conditions allowed us to identify 465 of the 473 objects (98.3%). (1) Observation time difference in less than 700 seconds. (2) Change ratio of the radius of circular orbit described in Eq. 1. of less than 0.1 ($a_0$ and $a_1$ are radiiuses of the circular orbit calculated from the data of each set). (3) Inclination difference of less than 1.0 degree. (4) RAAN difference of less than 1.0 degree. (5) Angular difference in position vectors of both sets at the central time of less than 5.0 degrees. These parameters were tuned to reduce incorrect identifications (false negative), but guarantee high matching rate which is more than 95%. 85 objects had a false partner with true one (false positive). In such cases, true one was subsequently selected by picking the one which has the better values of (2), (3), (4) and (5). There were three incorrect identifications (false negative).

Consequently, identifying the same objects from data of two sets of two sites is possible, which means the precise orbit of many LEO objects can also be feasibly determined using the proposed observation system.

5. Test Observation

As the observation simulation described in Sec. 4 showed the possibility of identifying the same objects from the data of two sets at two sites, we carried out a test observation to evaluate the orbit determination accuracy using actual observation data.

As we were unable to set up the entire system described in Sec. 3 at two sites, several catalogued LEO objects with available TLEs were observed at two sites, and their orbit was determined using only the observed data (TLEs were not used) as if the data had been captured by the system described in Sec. 3.

On July 27 and 28, 2012, 4 TLE-catalogued LEO objects were observed from Rikubetsu and Ishigaki observatories to mimic the observation described in Sec. 3. The observation equipment described in Sec. 2.1. and shown in Fig. 1. were used in both sites. Each object was observed at two separate sky regions on each site as described in Figs. 4 and 5. The orbits of the four objects were determined using data from the two sites on July 27. The SGP4[23] (Simplified General Perturbations Satellite Orbit Model 4) algorithm and the least squares method were used to determine the orbit, while data from the two sites on July 28 was used to evaluate the orbit accuracy. Although SGP4 simplifies some part of orbital determination, it is fast to calculate which will help to deal with numerous data in the proposed system. The orbits determined using data from two sites on July 27 were propagated using the SGP4 algorithm and used to calculate the object positions in the sky at the observed time on July 28. By comparing the actual observed positions with those calculated, the orbit determination accuracy of the system was evaluated. Table 1 describes the difference between the observed positions of the objects on July 28 at each site and those calculated using the orbit element derived from the data on
July 27 in arc seconds. dRA and dDec represent the differences in the direction of the right ascension and declination, respectively. The result of Table 1 shows that the orbital determinations are sufficiently accurate to track objects the next day using a normal optical sensor whose FOV is a few degrees, despite quite limited observation data. For objects with SSC numbers 13589 and 20720, the differences are less than 0.01 degrees, which indicate the optical observation system proposed in Sec. 3 is quite useful to determine the orbit of uncatalogued LEO objects.

### 6. Discussions

Although there are some works on optical survey of LEO objects, LEO objects are only monitored with radar observation system. This work showed that the proposed optical observation system will also be able to carry out this kind of job with much less cost. This is due to the enhancing detection efficiencies of optical sensors and PC performances.

As described in Secs. 1 and 2, there may be numerous uncatalogued LEO objects above the radar detection limit of 10 cm which may be attributable to the various radar reflection properties of spacecraft materials. Complementing the LEO survey system with optical sensors will be important for the future monitoring of the LEO environment.

Although the detection limit of 30 cm for the optical unit described in Sec. 2 may help detect uncatalogued LEO objects to some extent, lowering the limit must be desirable given the fact that most spacecraft cannot survive a collision with objects 1 cm in size. A small telescope of 18 cm is considered as a replacement for the camera lens. Although the FOV becomes narrower, the light collection ability is tripled. A CMOS camera was also considered for the new sensor. Although the CCD camera proposed in Sec. 2 has high sensitivity and low-noise properties, it is expensive and has a readout time of about 1 second, which is insufficient for fast-moving LEO objects. Recently, a CMOS camera has been developed and its sensitivity and noise level are catching up with those of CCD cameras. Besides, a CMOS camera is more cost-effective and has a much faster readout time (about 100 frames per second). We are going to develop a cost-effective and highly sensitive CMOS camera for LEO observation in the near future.

Image-processing technologies are also set to improve. Some image-processing algorithms and FPGA boards to detect faint GEO objects, invisible on a single CCD frame, have already been developed\(^{13, 14}\) and will be applied to numerous LEO observation data taken by CMOS cameras. By combining these improvements, it will be possible to detect uncatalogued LEO objects of less than 10 cm in size in the future.

This work showed that precise orbit determination of 143 objects was possible with 3 hours’ observation of two sites. The figure of 143 relates to catalogued objects, which means an almost equivalent number of uncatalogued objects in orbit would be determined if an optical system with a detection limit of 10 cm were developed. The usefulness of this value (143 uncatalogued objects in 3 hours observation) must be carefully evaluated. Number of monitored objects within a certain duration must be investigated. Optical observations of LEO objects are affected by the solar lighting condition and the weather. To maximize system efficiency, the site locations and/or the need for a third site must be considered. The orbit-determined objects must also be constantly monitored to maintain their orbit accuracies. A few telescopes specialized for tracking those objects will be required. These investigations are our future works.

### 7. Conclusions

The usefulness of a ground-based optical observation system for LEO objects monitoring was investigated. Data from two consecutive passes over the same objects were identified from bulk data taken at two longitudinally separate sites with high probabilities, which enabled us to determine the precise orbits of the detected LEO objects. A test observation showed orbit determinations using actual observation data assumed to be taken by the proposed observation system were sufficiently accurate to track detected objects the following day. Considering the detection limit of 30 cm for the unit, the optical observation network proposed in Sec. 3 can detect uncatalogued LEO objects and determine their orbits to some extent. Developing a sensor with high speed and high sensitivity like a CMOS camera and effective detection algorithms would lower the detection limit to less than 10 cm. An optical observation network using such technologies would contribute significantly to monitoring the LEO environment in future.
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