INVESTIGATION OF GROUND-BASED OBSERVATION SYSTEM FOR LEO OBJECTS

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ABSTRACT

We have examined the possibilities of ground-based optical observation system for LEO objects. Space environment is deteriorated with space debris especially in LEO region in recent years. The accuracies of TLEs are not good enough for the collision avoidance. Optical sensor has an advantage of being able to determine the positions of space objects in arc second's accuracy which will contribute the precise orbit determination and cope with the situation. The array of numerous optical sensor may be equivalent to the a radar observation system which is common for LEO observation. Although observable time for optical sensors are limited to 4-6 hours per day, the cost is much less than that of radar system. We carried out some simulations to evaluate the optical system. The simulations have shown that identical objects were recognized from the data of 4 individual equipments installed on 2 separate sites using the orbital elements of each object. This enables us to determine orbits of un-catalogued LEO objects precisely.

1 OPTICAL OBSERVATION SYSTEM FOR LEO DEBRIS

Figure 1. Optical observational unit which is composed of Canon 200mmF2 camera lens and FLI 2K2K back-illuminated CCD camera ML4240.

1.1 OBSERVATION EQUIPMENTS

The optical observation system for LEO debris consists of observation units and data analysis software. Fig.1 shows the unit which is composed of Canon 200mmF2 camera lens and 2K2K back-illuminated type CCD camera ML4240 manufactured by FLI. The FOV is 7.65 × 7.65-degree.

The transit times across the FOV of the objects in the altitude of 250km, 500km, 1000km, and 2000km are 4.3-, 8,8-, 18.5- and 39.5-sec, respectively on the assumption that the unit is observing the zenith. As the readout time of the CCD camera is 1.5-sec, the zenith pointed unit is able to observe 12 and 26 times for objects at 1000km and 2000km, respectively.

1.2 DATA ANALYSIS SOFTWARE

We developed the line-identifying technique for the data analysis[1]. Fig. 2 illustrates the technique. It 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 show 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

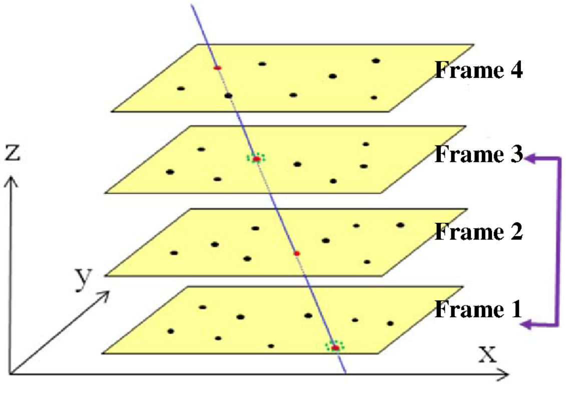

Figure 2. The line-identifying technique uses multiple CCD frames. First, it detects candidate objects (the black dots). Then, the technique finds any series of objects that are arrayed on a straight line in the 3-dimensional space. The *x*-, *y*- and *z*-axis of the 3-dimensional space are defined as the *x*- and *y*-axes of the CCD frames and the frame number, respectively.

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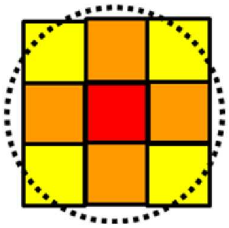

Figure 3. Brightness contour of the celestial objects

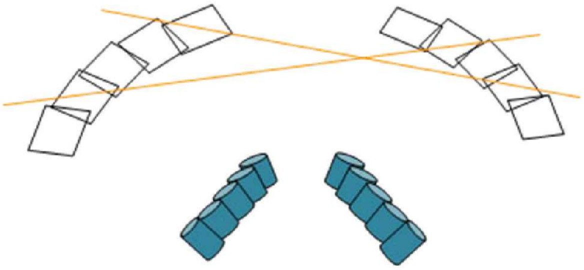

Figure 4. The array of the observation units at one site

the nine pixels in Fig. 3 divided by the central value. A shape parameter value close to “1” indicates that the central pixel is an extremely high value and may be noise. High values of the shape parameter represent signals from objects as shown in Fig. 3. Candidate objects are searched from the CCD frames by using a proper threshold, the proper shape parameter, and the condition that the values of the eight surrounding pixels are less than that of the center. When the threshold reduces and/or the shape parameter is near “1”, the number of candidates increases, which means a lot of noise pixels are counted as candidates. The way in which the number of candidates is decided is explained later. The candidates for each frame are detected using these processes.

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

Using this technique enables us to detect unknown space objects and near-Earth asteroids whose movements are unpredictable. The technique does not need to presume any particular target trajectory, as the stacking method does. The number of calculations depends on the number of candidates. For example, a commercial desktop computer (Dell Precision 450) is able to analyze 18 frames with 400 candidates in each frame in 7 minutes, which is quite acceptable. The user can select an appropriate number of candidates in each frame by considering the capability of the computer and the number of frames. With sufficient computing power, the number of candidates can be increased by lowering the detection threshold, meaning that darker objects will be detectable.

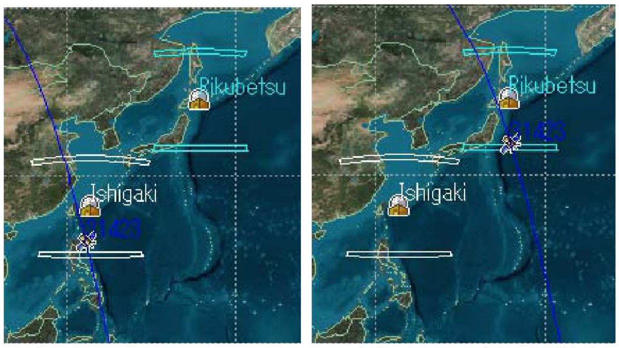

Figure 5. Two separate passes of the same object which are observed at two longitudinally separate sites.

Analyzing the data taken by the unit described in Sec.1.1 with the line-identifying technique, objects of 30cm in size at 1000km altitude are detectable. This detection ability is not enough since current detection limit is about 10cm. We are trying to acquire the ability which can detect objects of less than 10cm in size by modifying observation equipments and data analysis software in the near future.

2 OBSERVATION NETWORK

As the FOV of the observation unit is narrow(7.65 × 7.65-degree), detection and orbit determination of numerous LEO objects are difficult with one unit. Utilization of many units are considered. Main objective of this system is accurate orbit determination of detected objects. The past study showed observations of two passes which are carried out at two longitudinally separate sites and two 60-degree-separate observation at each site enable us to determine the orbit precisely[2]. In order to satisfy this demand, we considered the observation network as shown in Fig.4. and 5. Fig.4. illustrate the array of the observation units at one site. Many units are used to observe two narrow rectangle regions which are set to east-west direction. Fig.5. illustrate two separate passes of the same object which are observed at two longitudinally separate sites. This network is able to observe many LEO objects 4 times (2 times for each site).

In order to carry out precise orbit determination by using the network, the identification of same object out of many observation data taken by the network must be

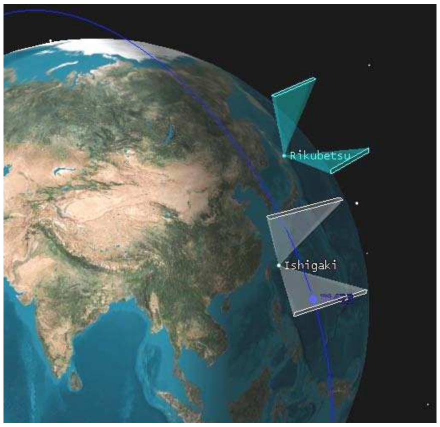

Figure 6. Observational simulation with the optical observation system for LEO objects.

done. In Sec. 3., the possibility of the identification, which is extraction of 4 sets of data of same object from many observation data taken at two sites are investigated using simulated data created by STK software.

3 SIMULATION OF OBSERVATION

First, two observation sites are chosen. A large portion of LEO objects reside in 800-1000km altitude. The orbital period of these objects is about 100 minutes. In order to observe the same object, which is observed at the first site, in almost the same direction at the second site, two sites should be separated about 25-degees in longitude which equals to the earth motion in 100 minutes. This time, Rikubetsu of Hokkaido prefecture (lat. 43.4565° N, long. 143.7660° E, alt. 363m) and Ishigaki of Okinawa prefecture (lat. 24.3745° N, long. 124.1390° E, alt. 179m) are selected as the observation sites.

As shown in Fig.5. and 6., 40 units of 3.5×3.5-degree's FOV are prepared for each site. The reason why units of 3.5×3.5-degree's FOV are used is mentioned later. The set of 20 units composes the FOV of 70-degree's east-west direction and 3.5-degree's north-south direction and directed to Az 0-degree and El 50-degree. Another set of 20 units composes the same FOV and directed to Az 180-degree and El 50-degree.

The observation time of Rikubetsu is from 8:40 to 11:40 (UT) on April 11th 2012. That of Ishigaki is from 10:20-13:20 (UT) on the same day which is 100-minutes later than that of Rikubetsu. 14574 TLEs opened by Space Track on April 11th 2012 are used. STK software calculated observation coordinates (RA and Dec) of each object at each site every second using these TLEs. Position errors of 0.005-degree which is 3 times of resolution of the equipment are considered. In the actual observation, we don't know the ID of the observed objects. We only get a lot of sets of times and coordinates. Therefore, identification of the same objects from the data of the 2 sets of each site must be the key whether this system is useful or not.

3.1 IDENTIFICATION OF SAME OBJECTS AT EACH SITE

Each site has two set of observation units. At Ishigaki, the first set directed to Az 0-degree and El 50-degree detected 872 objects in 3 hours' observation. The second set detected 636 objects. 473 objects were detected at both sites. Circular orbital elements are calculated from the data of each set. The conditions of the identification were investigated by comparing the observation time and the circular orbital elements. As a result, following 5 conditions enable us to identify 465 objects out of 473 ones (98.3%). ① Observation time deference is less than 700 seconds. ② Change ratio of radius of circular orbit described in Eq.1. is less than 0.1 (a_0 and a_1 are radiuses of circular orbit calculated from data of each set.). ③Inclination difference is less than 1.0-degree. ④RAAN difference is less than 1.0-degree. ⑤Difference of direction cosines at the central time of both sets is less than 5.0-degree. Although 14 objects got a false partner except true one, true one is selected by better condition of ③ and ⑤. Wrong identification did not occurred.

$$ar = \frac{|a_1 - a_0|}{0.5(a_1 + a_0)} \tag{1}$$

In the case of Rikubetsu, 916 and 934 objects were detected by the first and second set, respectively. 458 objects were detected by both sets. 454 objects were identified as the same objects using the 5 conditions (99.1%). 9 objects got wrong pair except true one but better condition of ③ and ⑤ enable us to select true one. One wrong identification occurred.

These results show that the identification of the same objects from the data of 2 sets of one observation site is possible by calculating circular orbital elements and using the 5 conditions.

3.2 IDENTIFICATION OF SAME OBJECTS AT BOTH SITES

154 objects were observed at both sites (two observations at each site). Circular orbits of 465 and 454 objects which are observed with the 2 sets of Ishigaki and Rikubetsu, respectively were calculated using the data of the 2 sets. As mentioned in Sec.3.1, The conditions of the identification were investigated by comparing the observation time and the circular orbital elements. As a result, following 5 conditions enable us to identify 143 objects out of 154 ones (92.9%). ① Observation time deference is from 5600 to 7700 seconds. ② Change ratio of radius of circular orbit

described in Eq.1. is less than 0.05. ③ Inclination difference is less than 1.5-degree. ④RAAN difference is less than 1.0-degree. ⑤ Difference of direction cosines at the central time of both sets is less than 90.0-degree. Although 85 objects got a false partner except true one, true one is selected by better condition of ②, ③, ④ and ⑤. 3 wrong identifications occurred.

As a result, identifications of the same objects from the data of 2 sets of 2 sites are possible which means precise orbit determinations of many LEO objects are feasible using proposed observation system.

4. DISCUSSIONS

Although Sec.3. showed the precise orbit determinations of many LEO objects are feasible, there are many problem to be solved.

Detection limit of the observation units described in Sec.1. is 30cm in 1000km altitude. In order to lower the limit, small telescope of 18cm will be considered in the near future. Although FOV becomes narrower, ability of light collection becomes 3 times. In the simulation of Sec.3., this telescope is considered for the observation equipment. FOV of one unit is 3.5×3.5-degree.

Although the CCD camera proposed in Sec.1. has a high sensitivity and a low noise property, it is expensive and its readout time is about 1 second which is not enough for fast moving LEO objects. Recently CMOS camera is being developed and its sensitivity and noise level are catching up with those of CCD camera. Besides, 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 high sensitive CMOS camera for LEO observation in the near future.

Image processing technologies are going to be improved. Some image processing algorithms and FPGA boards to detect faint GEO objects which are not visible on a single CCD frame have already been developed[3,4]. These technologies will be applied to a lot of LEO observation data taken by CMOS cameras.

The results shown in Sec.3. must be confirmed by the actual observation that two passes of a same LEO object are observed by two longitudinally separate sites, respectively and the orbit determination which is carried out using the data of the observation.

This work showed the precise orbit determination of 143 objects were possible with 3 hours' observation of 2 sites. The usefulness of this value must be carefully evaluated. Optical observations of LEO objects are affected by the lighting condition of the sun and weather condition. In order to maximize the efficiency of the system, site locations and/or the need of the third site must be considered. An orbit modification method of known objects using the data of a single site has been proposed recently[5]. The method will be applied to the proposed system. Effectiveness of the method will be evaluated in the near future.

5. CONCLUSION

The usefulness of ground-based observation system for LEO objects was investigated. Data of consecutive two passes of same objects were indentified from a lot of data taken at two longitudinally separate sites with high probabilities. This enable us to determine precise orbits of the detected LEO objects. High speed and high efficiency detector like CMOS cameras and effective detection algorithms will be developed to establish the proposed system in the near future.

6. REFERENCES

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