Activities of JAXA's Innovative Technology Center on Space Debris Observation

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ABSTRACT

The innovative technology research center of JAXA is developing observation technology for GEO objects in order to deal with the space debris problem. The center constructed a space debris observation facility at Mt. Nyukasa, Nagano in 2006. The observational facility contains two telescopes and two large CCD cameras. The main objective of the facility is to establish technologies of detection un-cataloged GEO debris and determination their orbits and apply theses technologies to Bisei Spacegurad Center in Okayama. At this moment, GEO debris detection software that can detect unresolved objects in CCD frames is being developed, and a new orbital determination method that can determine orbits of many GEO objects effectively is being tested. This paper presents the details of the facility and research activities.

1. INTRODUCTION

The Japan Aerospace Exploration Agency (JAXA) is studying observation technologies as part of the effort to deal with the space debris problems. JAXA's Innovative Technology Research Center constructed an optical observational facility at Mt. Nyukasa, Nagano in November 2006. As telescopes, CCD cameras, and analysis software came on line, the facility commenced routine observations to assist in the development of space debris observation technology. The detail of the facility, the CCD cameras and the observational software are described in section 2, 3 and 4, respectively. The analysis methods and orbital determination technique that are being developed and tested are discussed in section 5 and 6. Other research activities are shown in section 7.

2. MT. NYUKASA OPTICAL OBSERVATIONAL FACILITY OF JAXA

The Mt. Nyukasa optical observational facility with a relatively small 35cm telescope as its main equipment was built to aid in the development of observational technologies for high-altitude space debris such as that in geostationary (GEO) or geo-transfer (GTO) orbits. The main objective of the facility is to develop detection technology for space debris less than 10 cm in size. For the present, we aim to detect 20 cm-sized space debris in GEO with the 35 cm telescope. Although 1m telescopes are able to detect 10-20cm-sized (20th magnitude) GEO debris easily, sophisticated image processing is required to detect objects of this size with a 35 cm telescope. By

Fig.1. Mt. Nyukasa optical observational facility of JAXA

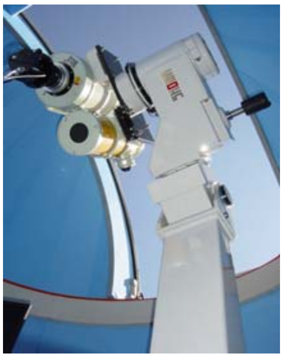
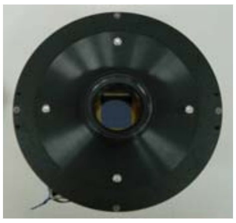


Fig.2(a). Eccentric elbow-type mount, 25cm and 16cm telescopes.

Fig.2(b). Fork-type mount and 35cm telescope



(a) Top view

(b) Side view

Fig.3. 2K2K camera

Fig.4. 4K4K-camera

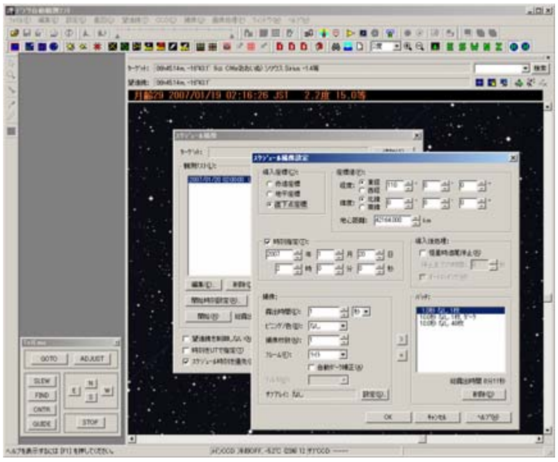


Fig.5. Debris auto-observational software

applying such processing to the data from a 1m telescope, detection of GEO debris less than 10 cm in size becomes possible.

The site is located at 1870 m altitude, which provides an outstanding optical environment. The site can detect dark asteroids of 22nd magnitude with the 35 cm telescope. Fig.1 shows an overview of the facility, which includes two domes, a control room, and two habitats. One dome has a 35 cm telescope, the other a 25 cm telescope. Fig.2 shows the observational equipment in the domes. An eccentric elbow-type equatorial mount that can hold two 25 cm telescopes is shown in Fig.2 (a). A fork-type equatorial mount supporting a 35 cm telescope is shown in Fig.2 (b). This telescope has contributed to the discovery of many new asteroids.

3. CCD CAMERAS

Three CCD cameras are used in this facility, a 1K1K-, a 2K2K-(Fig.3) and a 4K4K-camera (Fig.4). All the cameras contain back-illuminated CCD chips that have high quantum efficiencies at optical wavelengths. The 1K1K- and the 2K2K-cameras are cooled by Peltier devices down to 30 degrees below room temperature. The 4K4K-camera is cooled by circulating refrigerant down to -100 degrees in Celsius. Readout times for these cameras are fairly fast ranging from 4 to 10 seconds. As the typical exposure time is from a few seconds to 10 seconds for GEO debris observation, a fast readout time is required for observational efficiency. The fields of view of the 2K2K-camera with the 35 cm telescope, and of the 4K4K-camera with the 25 cm telescope are 1.3×1.3 degrees and 2.4×2.4 degrees, respectively.

4. OBSERVATIONAL SOFTWARE

Each telescope and its CCD camera are controlled by automatic debris-observing software. This software manages scheduled observations that specify coordinates of field of view, start times for exposures, exposure times, exposure mode, and number of CCD frames to be taken. The software executes all night observation automatically once it is set up. Fig.5 shows the setting of the schedule of the software. To determine the orbit of detected GEO debris with adequate precision, a measurement accuracy of 10 msec is required for the times of observation. The CCD cameras contain GPS devices that are connected to the sensor of the shutter for this purpose. The open and close times of the shutter are recorded in the image header with the unit of 0.001 second.

5. ANALYSIS METHOD

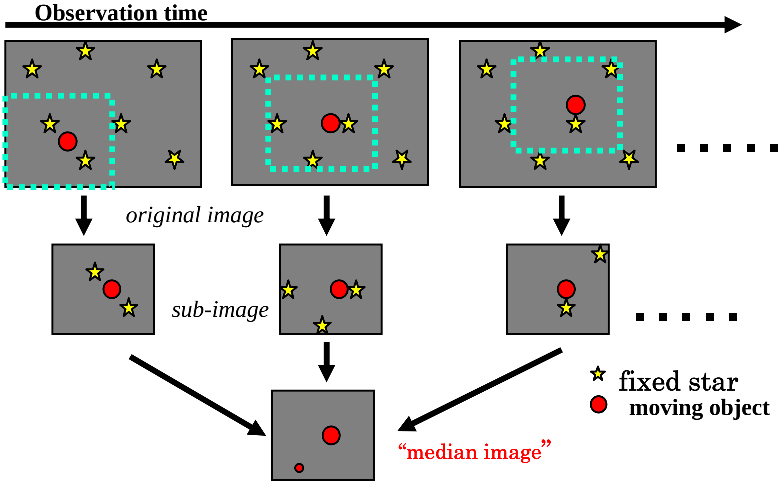
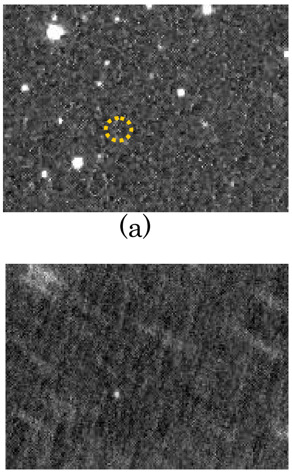


Fig.6. Stacking method


(a)

(b)

Fig.7. Asteroid detected by the stacking method

This section describes two analysis methods that are used at the Mt. Nyukasa optical observation facility.

5.1. THE STACKING METHOD

The stacking method uses multiple CCD images to detect very faint objects that are undetectable on a single CCD image. We have been developing this image processing, investigating its effectiveness and trying to utilize actual GEO debris observation since 2000 [1][2]. The general idea of this method is described below, and details are available in the references.

As shown in Fig.6, sub-images are cropped from many CCD images to follow the presumed movement of space debris. A median image of all the sub-images is then created. In this method, photons from the space debris arrive on the same pixels of the sub-images, and field stars are removed by taking the median because they appear in different places on each sub-image. Fig.7 shows an example of an asteroid detected using this method. Fig.7 (a) shows a part of one CCD image, and Fig.7 (b) shows the same region of the final image after the process was carried out using forty images. It is impossible to confirm the presence of the asteroid in Fig.7 (a), whereas the asteroid is bright and no field stars are shown in Fig.7 (b). The discovery of many new asteroids has proven the effectiveness of this method. The method enhances the detection ability of the 35 cm telescope to equal that of a 1 m telescope.

The only weak point of the stacking method is the time required to analyze the data when detecting an unseen object whose movement is not known, because a range of likely paths must be assumed and checked. Although main-belt asteroids and cataloged space debris whose movements can be estimated in some way are easy targets to detect, finding near-Earth objects and un-cataloged space debris is time-consuming work and not really practical. Using many PCs in parallel to reduce analysis time may be one solution. However, a hardware system purpose-built for this method, such as a field programmable gate array (FPGA) would be the best solution for use with an upcoming large-format CCD camera. As an FPGA is expected to reduce analysis time dramatically, efforts to translate this method to an FPGA system are underway at JAXA.

5.2. FPGA FOR THE STACKING METHOD

In order to reduce analysis time of the stacking method, we are developing FPGA system. Most time-consuming part of the stacking method is calculating median values of each pixel from the sub-images. As FPGA is a kind of

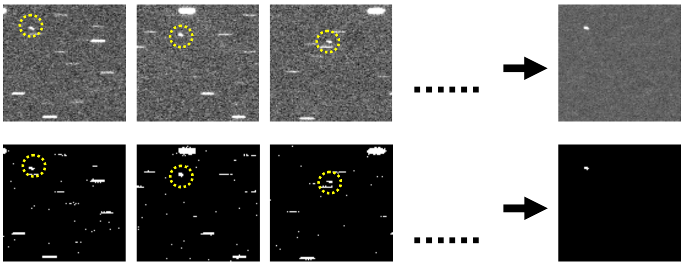


Fig.8. Deference between the original algorithm of the stacking method (upper) and the new algorithm using binarized images.

Fig.9. FPGA board H101-PCIXM manufactured by Nallatech

electrical circuits, it shows its power in simple calculations. More sophisticated and simplified algorithm is required for FPGA. We discovered that binarization of the sub-images with a proper threshold and calculating the sum of the binarized sub-image instead could derive almost the same consequence described in section 5.1. Fig.8 represents the difference between the original algorithm and the new algorithm. Calculating sum is much simpler than calculating median which has to sort individual value of each pixel and pick the median value, and very suitable for FPGA. Moreover, binarization itself reduces amount of data to one sixteenth which help to reduce analysis time a lot. We developed FPGA boards executing this algorithm. Fig.9 shows the FPGA board which is H101-PCIXM manufactured by Nallatech. The FPGA board is able to reduce analysis time to about a thousandth. This is a big progress. The FPGA board will be installed to the facility and used for actual observation in the near future.

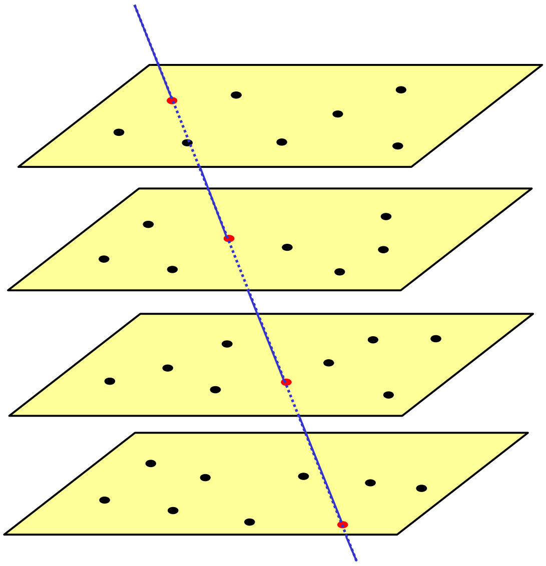


Fig.10. Line-identification technique

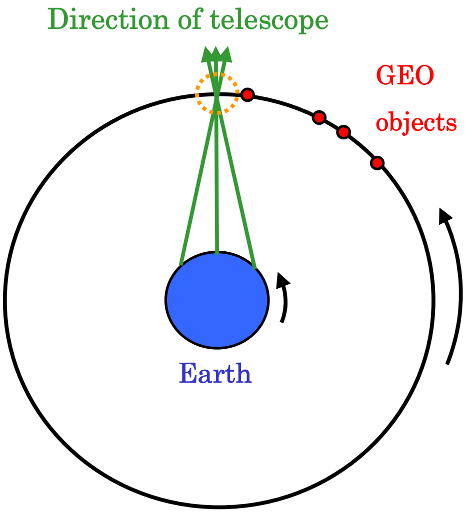


Fig. 11. Observation of one inertia position

5.3. LINE-IDENTIFYING TECHNIQUE

We developed the line-identifying technique to complement the stacking method. Fig. 10 sketches the technique, and the details will be described in the near future. The line-identifying technique uses many CCD frames as the stacking method does. First, it detects candidate objects (black dots in Fig.10) using a threshold and a shape parameter. Then, it finds any series of objects that are arrayed on a straight line from the first frame to the last frame. Appearing on a straight line as shown in Fig.10 means that an object is moving across the field of view at a constant velocity. Using this technique enables us to detect near-Earth asteroids and unknown space debris whose movements are unpredictable. The technique does not need to presume any particular movements of a target, as the stacking method does. The number of calculations depends on the number of candidates. For example, a commercial PC

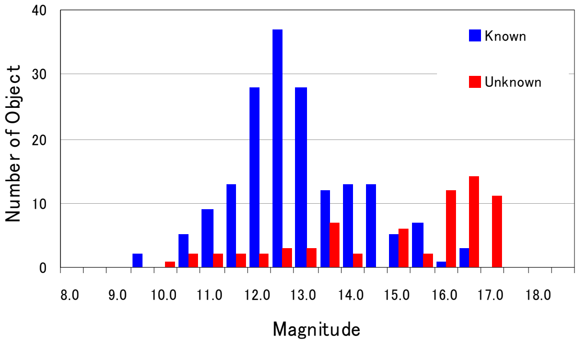


Fig. 12. Brightness distribution of cataloged (blue column) and un-cataloged (red column) objects.

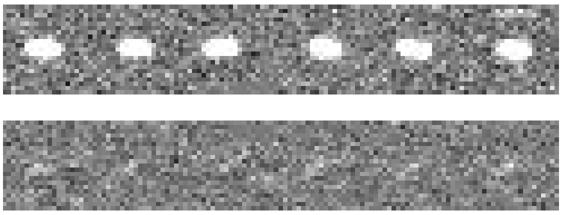


Fig. 13. Images of cataloged (upper) and un-cataloged (lower) objects that appear in data from the campaign. One is 12th magnitude and the other is 17th magnitude.

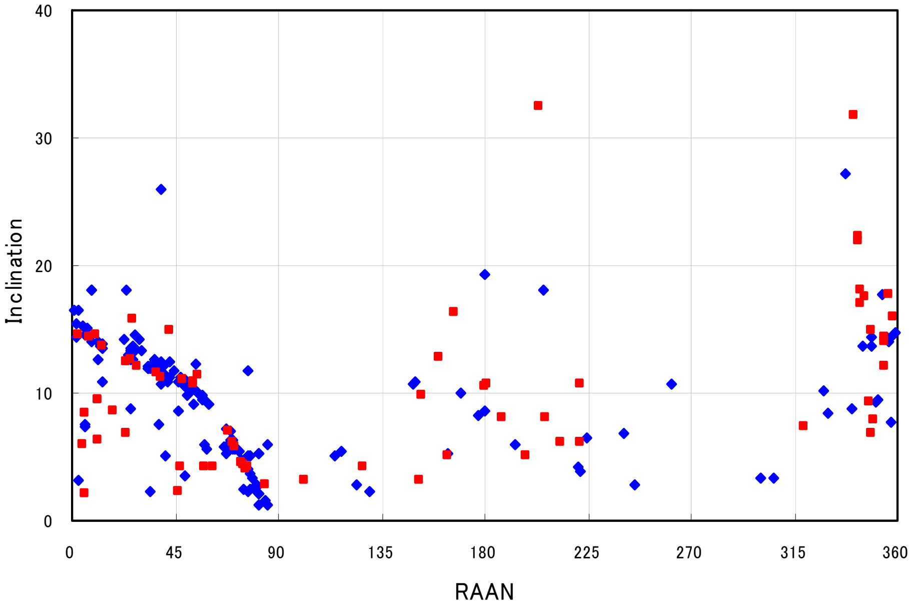


Fig. 14. Distribution of cataloged (blue column) and un-cataloged (red column) objects in the inclination-RAAN space.

(DELL Precision 450) is able to analyze 17 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 PC and the number of frames. If a PC has sufficient power, the number of candidates can be increased by lowering the detection threshold, meaning that darker objects will be detectable.

Although the line-identifying technique works efficiently in a practical analysis time, its ability to detect faint objects does not measure up to the stacking method. Its analysis time increases exponentially with the number of candidates on each frame. The same problem arises with the stacking method, but since line-identifying can cope with this by reducing the number of candidates, that technique will be used to analyze the actual observational data while the FPGA system is being developed for the stacking method.

6. ORBITAL DETERMINATION TECHNIQUE

After detection of space debris, the orbit of the detected target must be determined. A reliable orbital determination requires a long observational arc. However, the narrow field-of-view (FOV) of optical telescopes makes it difficult to re-acquire the same object after a few hours, especially in the case of eccentric orbits. To get a long arc, a telescope must follow one target for a long period of time. Therefore, determining the precise orbits of many GEO-crossing objects is very time-consuming, and is not an efficient use of telescope time. Umehara invented an observational method that observes numerous bits of space debris efficiently, using one telescope to cope with this situation [3][4]. The method utilizes a fundamental principle of orbital mechanics – an object in bound orbit always returns to the same orbit location after one complete revolution, if perturbation is negligible. This means if a telescope observes one specific inertia position for two nights, an object that passed through the field-of-view of the telescope in the first night must do so again in the second night (Fig. 11). From two nights' data, this method determines an approximate orbit that is accurate enough to predict the position of the target on the third night. Precise orbits are determined from three nights' data. Readers will find more detail on this method in the references.

We carried out a test observation to evaluate this method at the Mt. Nyukasa optical observation facility. One inertia position where a great deal of space debris was expected to pass through was monitored for three hours on each of two nights. On the first night, 20 objects were detected, and 18 on the second. Twelve objects were identified as twice-observed by comparing the elements of their presumed-circular orbits. For these objects, the positions on the third night were estimated from approximate orbits calculated from two nights' data. All the 12 objects were detected on the third night. Precise orbits were determined, and the standard deviations of o-c values (observed position – calculated position from the orbit) in right ascension and declination were a few arc-seconds and less than one arc-second, respectively.

7. OTHER RESEARCH ACTIVITIES

7.1. SURVEY OBSERVATION

In order to understand space environment around GEO region, survey observations are being carried out. One or two inertia positions in space are observed for one night observation. By observing many inertia positions for many nights, the space environment will be assumed. As describe in Fig. 11, observing inertia positions requires changing diction of the telescope many times during one night observation. The field of views of observation is changed every 5 minutes. 18 CCD frames are taken with 3-second exposure time in each field, and the tracking of the telescope is stopped during the exposure so that GEO objects exhibit point-like shapes on CCD frames. About 100 fields are observed for one night. All the data are analyzed with the line-identifying techniques described in section 5.2. Fig.12 shows the brightness distribution of detected GEO objects from the data of 15 days' survey. The blue and red columns represent cataloged and un-cataloged objects. The x-axis and y-axis show the brightness (magnitude) of detected objects and the quantity, respectively. Sample images of cataloged (12th magnitude) and un-cataloged (17th magnitude) objects that were detected from the survey data are shown in Fig.13. As can be seen from Fig.13, even with the line-identifying technique, fairly faint objects are detectable, although the stacking method has greater capability. Objects in geostationary orbit displaying a brightness of 16.5th and 17.5th magnitude are about 60cm and

Fig. 15. A part of CCD image where a streak of a GEO object is seen.

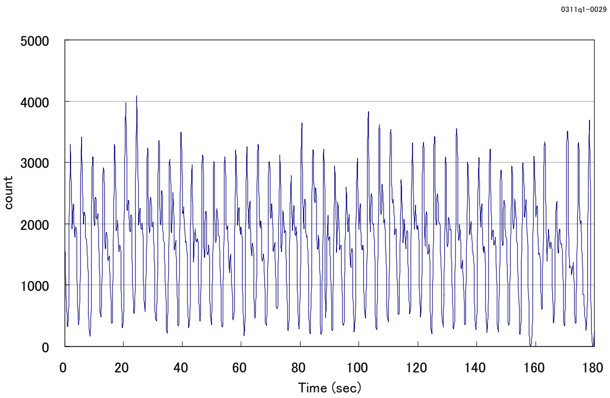


Fig. 16. The light curve of the object observed in Fig. 13.

40cm in size, respectively. Fig. 14 is the distribution of cataloged and un-cataloged objects in the inclination and RAAN space.

7.2. LIGHT CURVE OBSERVATION

Light curve observations of GEO and LEO debris are also being carried out. Light curves that are brightness changes along time give us the information about the motion and shape of space objects. The observation and data-analysis techniques are being developed. In GEO region, many light curves of GEO objects are obtained by observing the GEO belt with star-tracking mode. The telescope takes CCD images every 3 minutes. In CCD images, although stars show point-like shapes, GEO objects make streaks as shown in Fig. 15. By counting the value on CCD along the streak, the light curve of the object is obtained. Fig. 16 shows the light curve of the object taken in Fig. 15. By Fourier transferring the light curve data, the rotation period of the object is calculated. The rotation period of the object of Fig. 15 is about 3.7 seconds. The detail of the light curve observation of GEO objects is described by Kurosaki et al [5].

SUMMARY

The research and development activity at the Mt. Nyukasa optical observation facility is aimed at establishing technologies for the detection and orbit determination of un-cataloged objects. This paper describes how we are improving both the equipment and techniques to pursue this goal. Technologies developed here will be used at the Bisei Spaceguard Center where constant observations are carried out. One technology will be transformed this year.

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