Development of Faint Object Detection methods using optical telescopes

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1. Introduction
Since 1957, human beings have launched many satellites which has led to an increase in the number of artificial objects in orbit. Explosions and collisions of these objects create considerable volumes of space debris. For the safety of astronauts and satellites, space debris needs to be detected and cataloged.

For detection and orbit determination of space debris and development of advanced observation technologies, the National Aerospace Laboratory of Japan (NAL) has prepared ground-based optical telescopes. For LEO large debris, a high-speed tracking facility on board a 35 cm Schmidt Cassegrain telescope has been operational since 1999 and for GEO/LEO small size debris observation, a 35 cm equatorial-mounted telescope since 2001.

The development of automatic debris detection software is one of the most important research areas for space debris observation and some methods have been developed by NAL. One method is a technique called the “stacking method” which detects dark moving objects such as GEO debris, asteroids and comets. A large number of CCD images are cut out to match target movement and a median image is created from these sub-images. This process removes the effects of fixed stars and allows detection of very dark objects not visible on a single CCD image. We used this technique to analyze actual CCD images and confirmed its effectiveness.

We also propose a technique called the “line detection method” which detects invisible line effects on CCD images caused by LEO debris and meteors. In this technique, the direction of the line (i.e. traces of debris passing through the field of view) is supposed and values of pixels along the direction are accumulated to improve the signal-to-noise ratio.

The details of the stacking method are described in Section 2. We observed asteroids to investigate the effectiveness of the method. The observation and the results are presented in Section 3. The details of the line detection method and its probabilities are described in Section 4.

2. Stacking method
GEO debris, asteroids and comets move among fixed stars in the sky. For example, GEO debris moves around 15 degrees in an hour and the main-belt asteroids around 15 arc minutes in a day. GEO debris appears to hardly move in the sky for observers on earth whereas stars shift their positions in the sky via celestial motion.

Usual observation of GEO debris requires a short exposure frame (a few seconds) without equatorial movement of a telescope. Point sources as GEO debris in the frame are searched. If the exposure time becomes longer, the streaks caused by fixed stars obscure the detection of GEO debris.

Usual observation of asteroids requires two frames in the same region of the celestial sphere at a proper time interval with an equatorial movement of a telescope. These two frames are then compared to find moving objects among fixed stars. Exposure time is limited to about five minutes because of asteroid movement.

These processes do not detect dark objects under the one frame limiting magnitude. The stacking method uses multiple CCD images and enables detection of dark objects under the limiting magnitude of a single CCD image. As shown in Figure 1, sub-images are cut out from many CCD images to fit asteroid movement. A median image of all the sub-images is then created. In this method, photons from objects
Figure 2: An asteroid detected using the stacking method

(a) and (b) are accumulated on the same pixels of sub-images and fixed stars are completely removed by taking the median because they are moving on the sub-images. Figure 2 shows an example of an asteroid detected using the stacking method. Figure 2 (a) shows part of one CCD image and Figure 2 (b) the same region of the final image after the process has been carried out. Forty images are used. It is impossible to confirm the presence of an asteroid in Figure 2 (a), whereas the asteroid is bright and no fixed star exists in Figure 2 (b). Background noise was reduced as in Equation (1).

\[
\sigma_{\text{median}} = \frac{1.2}{\sqrt{N}} \sigma_{\text{individual}}
\]  

(1)

Here \(N\) is the number of sub-images used to make up a median image. This means darker objects are detectable as more images are used. The factor 1.2 is calculated from Monte Carlo simulations.2)

3. Observation of asteroids and results

We tried test observation of the stacking method to investigate its effectiveness. Asteroids are good targets for test observation because many asteroids of various magnitudes are cataloged. The observation was carried out on January 12 and 13, 2002 at Mt. Nyukasa Astronomical Observatory founded by amateur astronomers in Nagano Prefecture, Japan. NAL set up a 35cm Newtonian telescope ε 350N manufactured by Takahashi Co. Ltd. and a 1K \( \times \) 1K back-illuminated CCD camera FCC-104B manufactured by N.I.L. Co. Ltd. for the development of the GEO debris and asteroid observation technology and data analysis process. Total sky coverage of the image area of the system is around 0.61\( \frac{\text{deg}^2}{\text{deg}^2}\). The telescope and the camera shown in Figure 3 were used for the observation. We observed two main-belt regions. The coordinates of the regions were R.A. = 07:26:34, Dec = 21:59:13 and R.A. = 07:24:05, Dec = 22:00:36.9. Forty images were taken with three
minutes exposure time. The limiting magnitude of one frame was 18.7 in \( V \) band.

As a result of analyzing data acquired over two nights and two regions using the stacking method, we detected 10 known asteroids and 11 unknown asteroids. The limiting magnitude was 20.5 in \( V \) band. Five unknown asteroids were detected in data acquired over two nights. We reported the five asteroids to the International Astronomical Union (IAU) and received registration numbers. All five asteroids are darker than 20th magnitude. This is the asteroid ever detected in Japan and it is the first time in the world that such dark asteroids have been detected with a small aperture telescope (35cm in diameter). The details of the detected unknown asteroids are given in Table 1. By using forty images, the stacking method can detect asteroids about two magnitudes darker than the normal method.

From the results of observation, we can calculate the detectable size of GEO debris with this method. The Japan Space Forum founded the Bisei Spaceguard Center (BSGC), in Okayama Prefecture which is used solely for the observation of space debris and NEOs (Near Earth Object)\(^4\). When the one-meter telescope and the back-illuminated CCD camera at BSGC are used for observation of GEO debris, it is estimated it will detect 10cm-size GEO debris using the stacking method.

### Table 1. Details of detected asteroids

<table>
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<th>Time(UTC)</th>
<th>R.A.</th>
<th>Dec</th>
<th>Mag</th>
<th>Number</th>
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<tr>
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<td>7 23 32.3</td>
<td>22 03 06.9</td>
<td>20.1</td>
<td>2002AH180</td>
</tr>
</tbody>
</table>

### 4. Line detection method

LEO debris makes a streak on a CCD image. Even if invisible on the CCD image, the effect of the streak remains. We are developing an image processing technique, the line detection method, to extract the effect of the streak created by LEO debris. Figure 4 shows the process of the line detection method. Figure 4 (a) is a raw CCD image. The white spots are fixed stars. In this image, no lines are observable at a first sight. Fixed stars are first removed by masking or subtracting a sequent image (Figure 4 (b)). Then the image is rotated at a proper angle and the effective region with no influence from the rotation process is cut out (Figure 4 (c)). Finally the median values of all pixels of every line along the green arrow are calculated (Figure 4 (d)). The last two parts of the process (Figure 4 (c) and Figure 4 (d)) are repeated for every angle to detect weak invisible lines.

Figure 5 shows one line effect detected in the image by using the line detection method. The horizontal and vertical axes show pixel numbers perpendicular to the direction and the values of each pixel respectively. Proper values are added to upper two lines for easy understanding. The bottom line shows the noise level of a raw CCD image. The middle one shows the median values of every 20 pixels along the direction. The line effect is visible at the center. The top one shows the median values of all pixels along the direction. The effect is very clear (at the red arrow). From the rotation angle and the coordinate of the effect, the actual position of the detected line is determined as shown in Figure 4 (e).

The pixel number along one direction of recent CCD cameras is about a few thousand. Equation (1) indicates we can detect LEO debris from 30 to 40 times darker than with the normal method. When the one-meter telescope and the back-illuminated CCD...
camera of the BSGC are used for the observation of LEO debris, they are expected to detect 3cm LEO debris at 200km, 6cm debris at 400km and 10cm debris at 1000km using the line detection method.

5. Conclusions

Two image processing techniques, the "stacking method" and the "line detection method", were proposed and investigated for practical use. From observation at the Mt.Nyukasa Astronomical Observatory, five unknown asteroids darker than 20th magnitude were detected using the stacking method. It is the first time in the world that such dark asteroids with a small aperture telescope (35cm in diameter) have been detected. We also confirmed that the line detection method worked efficiently on the actual CCD images. These techniques should prove to be powerful tools to detect unknown small space debris.

Reference


(4) Isobe, S. and Japanese Spaceguard Association.; Japanese 0.5m and 1.0m telescope to detect space debris and near-earth asteroids, Advances in Space Research, Vol.23, pp.33-36, 1999.