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An adaptive threshold method for improving astrometry of space debris CCD images

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Abstract

Optical survey is a main technique for observing space debris, and precisely measuring the positions of space debris is of great importance. Due to several factors, e.g. the angle object normal to the observer, the shape as well as the attitude of the object, the variations of observed characteristics for low earth orbital space debris are distinct. When we look at optical CCD images of observed objects, the size and brightness are varying, hence it's difficult to decide the threshold during centroid measurement and precise astrometry. Traditionally the threshold is given empirically and constantly in data reduction, and obviously it's not suitable for data reduction of space debris. Here we offer a solution to provide the threshold. Our method assumes that the PSF (point spread function) is Gaussian and estimates the signal flux by a directly two-dimensional Gaussian fit, then a cubic spline interpolation is performed to divide each initial pixel into several sub-pixels, at last the threshold is determined by the estimation of signal flux and the sub-pixels above threshold are separated to estimate the centroid. A trail observation of the fast spinning satellite Ajisai is made and the CCD frames are obtained to test our algorithm. The calibration precision of various threshold is obtained through the comparison between the observed equatorial position and the reference one, the latter are obtained from the precise ephemeris of the satellite. The results indicate that our method reduces the total errors of measurements, it works effectively in improving the centering precision of space debris images.
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Keywords: Space debris; Astrometry; Image-processing; Optical observation

1. Introduction

Space debris is defined as non-functional artificial objects of all sizes in near-earth space (Schildknecht, 2007). Since first man-made satellite 'Sputnik-1' was launched in 1957, the problem of space debris came up accordingly. Nowadays, space debris has been recognized as a serious danger for operational spacecraft and manned spaceflight (Xu and Xiong, 2013). The growing population is an increasing threat for future space operations. To avoid the collision risk and assure the safety of space missions, such objects should be observed and catalogued consecutively. Surveys utilizing optical ground-based telescopes are feasible and realistic for space debris detection (Matney et al., 2004), several organizations have developed their observing strategies and reduction approaches, and the related results are also published (Alby et al., 2004; Musci et al., 2004, 2005; Porfilio et al., 2004; Molotov et al., 2008; Olmedo et al., 2011).

The data reduction of optical space debris observation has several similarities with the one adopted for surveying near Earth objects (minor planets, comets and asteroids, etc.). According to Popowicz et al. (2013), a light from a

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star, is blurred by several factors during imaging process, e.g. the atmosphere and the optical system, the object image can be best described by a point spread function (PSF). Usually the PSF can be modeled by the Gaussian surface for a high quality telescope system while the exposure time is long enough. However, low earth orbital space debris moves with angular velocities much higher than near-Earth objects, hence the phase angle (the angle between the observer and the Sun from the object), the distance as well as the altitude of object (generally the spinning period of space debris is several seconds) are variable during exposure, which make the observed characteristics of debris CCD images changing over time, sometimes the variation of apparent magnitude can be up to 2. Meanwhile, during observation the telescope should move fast to track the object, the instability of telescope during fast moving makes the tracking error significant, and the relative movements between object and background stellar limit the exposure time, hence the imaging process of debris CCD images is affected. Furthermore, surveying space debris requires large field of view for telescope, it leads to under-sample inevitably (Lauer, 1999). These factors make it difficult for precise astrometry.

One of the most important aims of astrometry is obtaining the precise position for celestial objects, and the application of CCD centering algorithm is crucial for reduction accuracy. Stone (1989) took into account five one-dimensional centering algorithms, including symmetric Gaussian, modified moment, etc. and investigated their performances on synthetical produced star images, he demonstrated that while the sky-background level was significant, the modified moment approach which suppressed the sky background below a chosen threshold was best. Ji et al. (1996) and Ji and Wang (1996) derived the similar results later. Li et al. (2009) analyzed two-dimensional Gaussian algorithm, as well as several approached above, by means of CCD images taken by the 1 m telescope at Yunnan Observatory, the results showed that the two-dimensional Gaussian exhibited a relatively high centering accuracy for faint stars as well as bright ones, which was confirmed later by Sun et al. (in press). Besides these classic approaches, some other centering algorithms were introduced in application, e.g. maximum likelihood method (Lu, 1993) and cubic spline interpolation (Platais, 1991), and some specific techniques were also developed for astrometry of planets in solar system and their satellites (Peng et al., 2003; Peng, 2005).

The threshold indicates the level above which the pixels are treated as if they are part of objects, and usually the threshold is chosen greater than the background level. However, it has not been derived yet how to choose the best threshold during data reduction. Generally the threshold is applied empirically, there are two ways to implement the threshold, one is taking the threshold value at $n\sigma$ level above the smoothed background level, where σ is the fluctuation level of smoothed background and n is a factor given, this way is adopted by Stone (1989) and several public software packages, e.g. Sextractor (Bertin and Arnouts, 1996); the other is given in the form $V = m + (M - m)n$, where V is the threshold value, M is maximum gray level of the chosen pixels and m is the minimum one, n is the coefficient given, as adopted by Peng et al. (2008). Both two threshold methods should set the value of factor n, and during application this factor is given as a constant. In space debris observations, the data should been handled in real time, due to the fast object movement, the apparent brightness and geometric size of object CCD images are variant with time, hence it's not suitable and efficient to set an empirical constant coefficient during data reduction. To improve the precision of data reduction, the application of threshold should be considered cautiously.

In our paper an innovative threshold method is presented. This method takes the estimation of signal flux as threshold, and divides an initial pixel into several sub-pixels by cubic spline interpolation, at last the threshold is applied to the sub-pixels. The detail of our method is shown in Section 2, and the application is described in Section 3. Section 4 summarizes the results and discussions of our test and in Section 5 we draw the conclusion.

2. Image processing pipeline for LEO objects

The dedicated telescope for surveying space debris generates a large volume of data due to the high frame-rate, the data requires an automated processing pipeline to detect, measure and extract object parameters. The pipeline should address the challenges arising from the observations, such as the variations of image noise and flux. The main parts of data processing including the innovative threshold approach are described here step by step. The processing pipeline below is dedicated to reduce the CCD images of space debris, and the first several steps are similar to the ones used by Sun et al. (2013b).

1. In observations some apriori information about the object can be provided, such as the extrapolated ephemeris and the relevant projected CCD coordinates (x_0, y_0) at observed time, according to the survey strategy, the object tracking is applied and the image of object appears as point. It should be noticed that the (x_0, y_0) are estimated, the deviations between (x_0, y_0) and the true values may be up to several pixels, caused by the errors of the apriori information. We first set a slide window on initial CCD frame, the window is centered at the projected coordinated (x_0, y_0). Generally the window size is 24 pixels × 24 pixels, and it can be set as any other suitable value, considering the geometric size of object image.
2. A simple modified moment is implemented to obtain another centroid value (x_1, y_1)

$$\begin{cases} x_1 = \dfrac{\sum_x \sum_y xM(x,y)}{\sum_x \sum_y M(x,y)}, \\ y_1 = \dfrac{\sum_x \sum_y yM(x,y)}{\sum_x \sum_y M(x,y)}, \end{cases} \tag{1}$$

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