An Improvement of Stars' Centroid Determination using PSF-fitting Method

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***Abstract*—This paper presents an algorithm for restoring telescope images corrupted by turbulence effects and readout noise of a telescope system in order to determine centroid positions of stars, especially position of a reference star. A computation method relying on an accurate centroid estimation algorithm reconstructing a point spread function (PSF) from registered telescope images has been used. Minimisation of turbulence effects and telescope control system noise in long term images acquired and registered by the ground telescope is proposed. A solution of the distortion error minimisation signal is dedicated to GoTo calibration procedures built in control mechanisms of the electromechanical telescope system. Proposed method has been verified in Matlab environment for real deep sky images registered by the ground telescope system.**

Keywords*—*centroid estimation; PSF fitting; image processing

I. Introduction

Astronomical images acquired and registered by the ground telescopes are distorted by several sources. Atmospheric turbulence effects, readout noise and non-idealities in telescope mechanisms are dominant sources of the telescope image distortions. Adaptive optics (AO) system of the telescope is used to restore real images. The aim of the AO is to filter the distortions from the deep sky image and to generate a compensatory signal to control a telescope corrector [1, 2]. Determination of a star position called a centroid detection is one of the main AO tasks. Position of a reference star is determined as the first task and then positions of the other stars in the telescope image are determined according to the position of the reference star [3]. Centroid detection has to be preceded by filtering of image distortions. Many different computation methods are adopted to reduce image distortions. Mathematically simplest methods are based on computing the centre of mass [4] and the weighted centre of mass [5-7] of a star, respectively. A Gaussian pattern matching [8] is also used in centroid detection. Very popular centroid detection algorithms rely on turbulence prediction methods adopting Zernike polynomials [9] and principal component analysis with Kalman filtering [10]. Those methods are time consuming, particularly if a polynomial degree is high. Turbulence prediction may be determined by a Bayesian estimation theory [11], too.

Proposed method of centroid detection of deep sky stars in the telescope images is based on generation of an error minimisation signal to compensate turbulence effects and readout noises in deep sky images registered by the ground telescope system. In paragraph 2, the effect of the atmospheric turbulence and equipment noise on the quality of telescope images is described. A computation method relying on an accurate centroid estimation algorithm reconstructing a point spread function (PSF) from registered telescope images is presented in paragraph 3. Simulations of astronomical images before and after correction are illustrated in paragraph 4. For verification purposes, the obtained results are compared to results obtained by standard method and presented in paragraph 5.

II. Effect of Atmospheric Turbulence and Equipment Noise on Centroid Accuracy

A. *An influence of the atmosphere turbulence*

A small amount of light reaches a telescope CCD detector. Therefore a long time exposure to light is required to acquire and record astronomical images. The same fragment of the sky has to be registered by the telescope CCD detector even for several minutes.. To satisfy that requirement, the ground telescope position should be corrected to compensate the earth revolving movement. A correction of the telescope position depends on a geographic position of the telescope and a position of an observed sky object. Regardless of the appropriate correction of the telescope position, astronomical images have to be filtered for different sources of distortions such as turbulence effects, CCD detector noise and telescope mechanical vibrations.

Atmospheric turbulence effects are dominant sources of telescope image distortions. The distortions are caused by the following effects: differences in air density and temperature on different altitudes, movement of masses of atmosphere, pollution by cosmic dust and gases. The atmospheric sources of image distortions are also lights from nearest neighbourhood such as street and advertisements lights, flare-up and reflection lights.

CCD detector noise follows the Poisson statistical distribution rule. Signal to noise ratio increases with the increase in the arrival rate of photons at the CCD detector. Dark fragments of the image are more noisy than bright ones. To achieve better quality images, a long light exposure time of the CCD detector has to be applied.

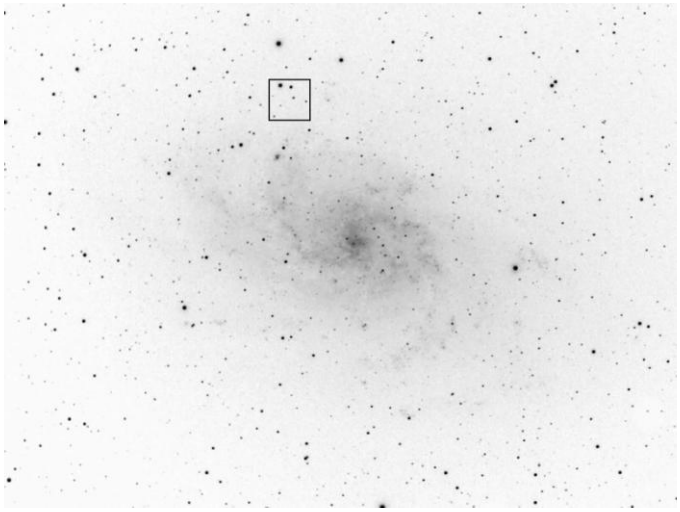

Fig. 1. Picture of the M33 Galaxy, a group of stars are marked and chosen for the next calculation. Picture: Robert Suszynski, refractor SW80ED 80/600mm, camera SBIG ST-2000XM, stacking of 13 images with exposure 300 s, each.

Telescope mehanical vibrations are caused by telescope drives, gust of wind, fast temperature changes and precipitations. A precise montage of the drives-telescope-camera CCD system leads to significant reduction in mechanical vibrations and their influence on astronomic image distortions.

Reduction of atmospheric turbulence effects on astronomic image distortions is a very difficult task. In this paper, a novel method to compensate atmospheric turbulence effects in AO system is proposed.

III. PSF Fitting

Conditions of observations in one session are usually the same or very similar. Weather conditions, atmosphere turbulences and telescope system have permanent parameters that have made a direct impact on distortions of registered astronomical images. They may be characterized by the PSF function describing blurry images on a group pixels[12-15]. The PSF function can be expressed by the following equation

$$\mu(x,y) = \frac{1}{2\pi\delta} exp\left[-\frac{(x-X)^2+(y-Y)^2}{2\delta^2}\right] \qquad (1)$$

where δ denotes standard deviation, X and Y denote coordinates of the highest value centre point.

The PSF function may be determined numerically from an analysis of registered images. It describes image distortions as a result of atmospheric conditions and the parameters of registering equipment for particular observation session and may be used to perform subsequent images. This result allows to use PSF-fitting method to determine positions of stars on subsequent registered images.

To improve determination of stars' centroids, an utilisation of PSF-fitting method [16, 17] is proposed. In particular observation session, a test image is acquired and registered in order to determine current function PFS describing atmospheric conditions and registering equipment. The test image is performed several times and averaged PSF for several stars is calculated as a pattern function. Calculations of the averaged PSF are time consuming, but performed once at the beginning of the observation session.

IV. Image Co-ordinate Measurements

A procedure of centroid determination in AO systems and simple auto-guiding systems results in coordinates of stars in registered image. The coordinates have to be computed precisely in real time, before the next image is acquired.

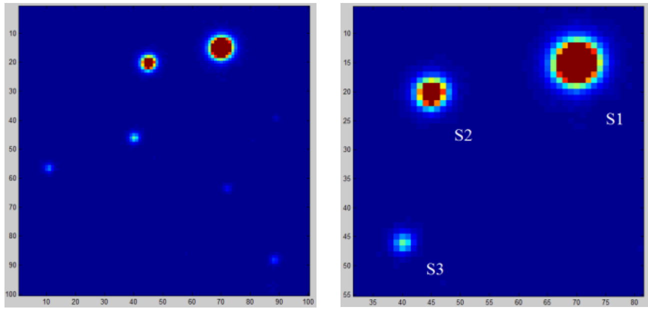

Fig. 2. (a) A group of stars chosen for reconstructing the PSF and (b) stars S1, 2, S3 chosen for next calculation. Source: Own Matlab calculation.

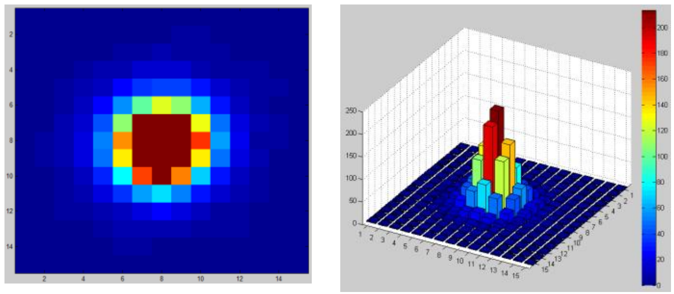

Fig. 3. The star number 2. An example of PSF for bright star. Source: Own Matlab calculation.

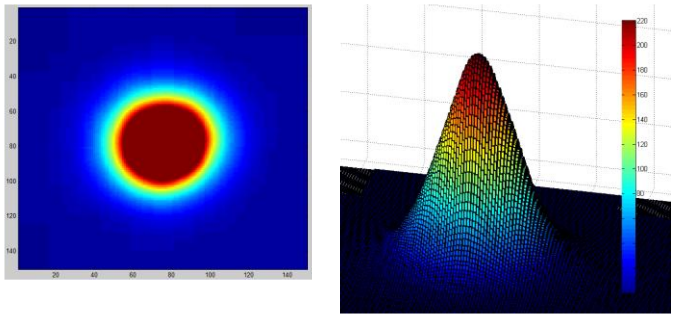

Fig. 4. The reconstructed PSF function using for next calculation in PSF-fitting method. Source: Own Matlab calculation.

V. Results using Real Data

A. *Investigated objects*

Proposed method of centroid determination based on PSF-fitting have been tested on images of real astronomical objects. Detailed data of thirteen images of M33 Galaxy, shown in Fig. 1, have been used to perform calculations. The images have been acquired by monochromatic astronomy camera ST-2000XM and telescope SkyWatcher 80ED with aperture: 80mm and focal length: 600mm on parallactic montage EQ6 SynScan. Every image has been registered in 300 seconds. Series of images have been registered during one night, in the same weather conditions, by the same telescope system.

B. Calculation of stars' centroids

To verify the proposed method, extra calculations for two standard methods based on computing a centre of mass and a weighted centre of mass of a star have been performed. Computations have been performed for three stars denoted S1, S2 and S3 and shown in Fig. 2. The stars have different relative brightness. The brightest S1 is registered on 15x15 pixels area. Its central part is white, because its value exceeds a maximum value of 16 bit CCD converter. The S2 is registered in a whole range of CCD dynamics and its shape has sharp edges. The darkest S3 is registered indistinctly, because 300 seconds is too short a time to obtain enough light for this star. The S3 has been chosen to test described methods in a case of dim stars.

To create reference data for three tested methods, a calibration procedure of a series of thirteen M33 images has been made. Flats, dark and bias pictures have also been taken into consideration. During the calibration process, a correlation of images, using 126 stars, has been done. Proposed method is reliable, but requires complicated calculations and cannot be done in real time systems. After calibration, we received data about movement between images from the series.

Star brightness threshold cut off is taken into consideration in a method based on computing the centre of mass of a star. In the second method, using weighted centre of mass of a star, such cut off in not necessary. The weight represents brightness of each pixel inside the star contour. To determine star centroid, both methods are using a computation of the center of mass of a plane figure. Examples of star contours for both methods are presented in Fig. 3.

Suitable computations of above mentioned methods have been performed for a series of thirteen test images of M33 galaxy and presented in Tab. 1. For simplification, only the position shift in coordinate x is presented. Relative shifts are calculated in relation to the image number 7.

C. PSF-fitting method

The calculated averaged PSF shown in Fig. 4 is used when subsequent images are acquired. Resolution of averaged PSF is 10x10 times greater than the resolution of registered images. It allows a 10x10 times increase in accuracy of stars coordinates on subsequent images. In order to determine star position, the averaged PSF is correlated with star image in area of few pixels of expected position of the star. Obtained maximal image correlation value is used to determine shifted position of the star. Calculations are not time consuming and may be implemented in real time for several stars. Application of greater resolution of averaged PSF allows to obtain star centroid calculations with 1/10 pixel accuracy and to reduce turbulence effects, CCD detector noise and telescope mechanical vibrations. Results of the accuracy of centroid determination obtained by the proposed method and two standard methods for reference, for a series of thirteen real images of M33 galaxy are presented in Tab. 1.

VI. Conclusion

In this paper we proposed an algorithm for restoring telescope images corrupted by turbulence effects and readout noise of a telescope system in order to determine centroid positions of stars. A computation method has been used which relies on an accurate centroid estimation algorithm, reconstructing a point spread function (PSF) from registered telescope images.

TABLE I. ACCURACY OF CENTROID DETERMINATIONS FROM STANDARD AND PSF FITTING METHODS

Pic. No.	**Centroid determination method**									
	Centre of mass **Δ*x* [pixel]**			***Weighted centre of mass*** **Δ*x* [pixel]**			***PSF-fiting*** **Δ*x* [pixel]**			***Refer.*** **Δ*x* [pixel]**
	S1	S2	S3	S1	S2	S3	S1	S2	S3	
1	-3.91	-4.00	-4.00	-3.52	-3.07	-0.77	-4.00	-4.00	-4.00	-3.91
2	-3.15	-3.31	-3.00	-3.01	-2.63	-0.75	-3.30	-3.30	-3.30	-3.39
3	-2.65	-2.60	-3.00	-2.43	-2.16	-0.71	-2.60	-2.80	-2.70	-2.91
4	-1.96	-2.00	-2.00	-1.85	-1.66	-0.62	-2.00	-2.10	-2.10	-2.08
5	-1.28	-1.09	-1.00	-1.25	-1.10	-0.44	-1.50	-1.30	-1.30	-1.49
6	-0.79	-0.76	0.00	-0.66	-0.59	-0.50	-0.60	-0.80	-0.60	-0.88
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.45	0.91	1.00	0.58	0.56	0.26	0.50	0.70	0.70	0.42
9	1.36	1.43	2.00	1.22	1.11	0.58	1.40	1.40	1.40	1.38
10	1.88	2.00	2.00	1.82	1.64	0.74	2.00	2.00	2.20	1.98
11	2.39	2.91	3.00	2.42	2.23	1.12	2.50	2.70	2.80	2.63
12	3.22	3.25	4.00	3.00	2.71	1.26	3.20	3.40	3.50	3.27
13	3.65	4.00	4.00	3.54	3.23	1.56	3.70	4.00	4.20	3.88

Own calculation on Matlab program

Computed results for the proposed method, two standard methods and reference data are presented in Tab. 1. The first standard method - centre of mass - is ilustrated in Fig. 5. Presented results exhibit small accuracy and large errors for dim star. The second standard method - weighted centre of mass - is ilustrated in Fig. 6. Presented results exhibit better accuracy, but also large errors for dim stars. Best results illustrated in Fig. 7 are obtained for proposed PSF-fitting method. Determination of PSF-fitting function at the beginning of image acquisition results in precise calculation of stars positions in a whole series of analysed images. Obtained results correspond to the reference data of all kinds of stars: S1, S2 and S3.

The proposed method gives the best results. PSF-fitting could be used in the callculation of star's centroids in real deep sky images. This method is not time consuming and it is applicable in real time FPGA circuits.

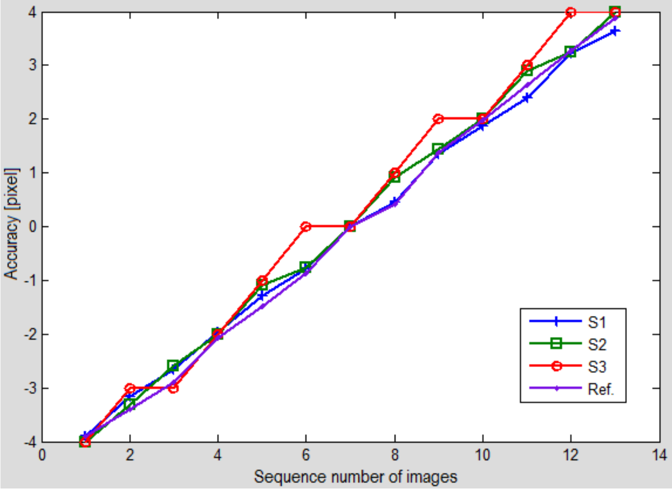

Fig. 5. The accuracy of centroid determination for centre of mass method. Results for three different stars S1, S2, S3 and reference calculation.

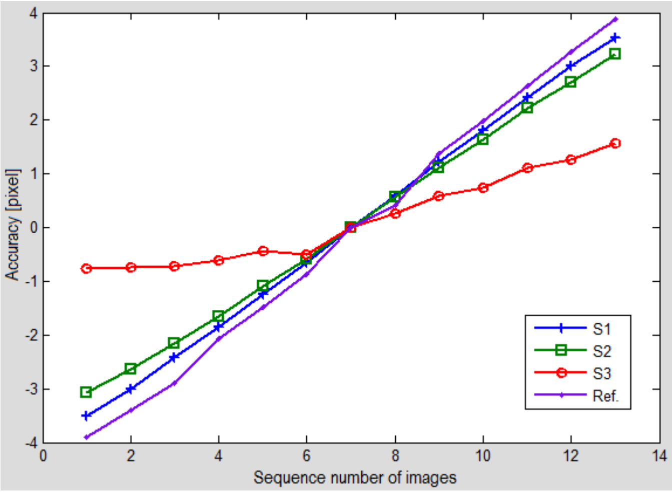

Fig. 6. The accuracy of centroid determination for weighted centre of mass method. Results for three different stars S1, S2, S3 and reference calculation.

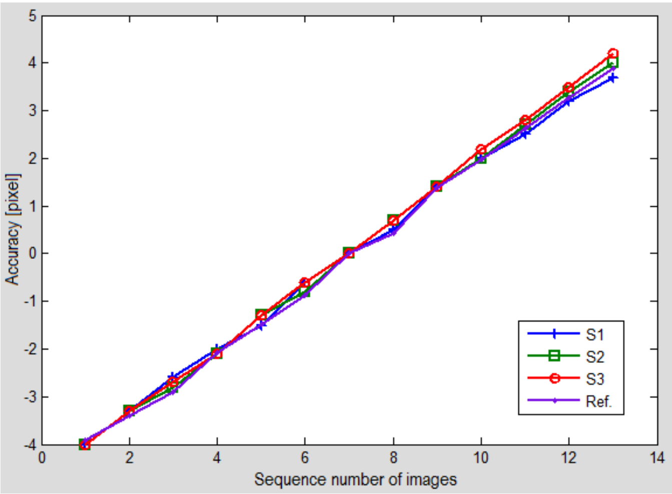

Fig. 7. The accuracy of centroid determination for PSF-fitting method. Results for three different stars S1, S2, S3 and reference calculation

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