Applications and Technical Research of Astrometrica and MaxIm DL in Astrometry (Postprint)

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Abstract

To investigate the application and processing differences between the Astrometrica and MaxIm DL software packages in astrometry, this paper presents a detailed comparative and technical study covering aspects such as the general overview of both software, CCD image reading/writing and transformation, flat-field correction processing, parameter configuration, reduction, and stacking. Using two sets of observational data of the M35 star cluster obtained with the 1m optical telescope at the Yunnan Observatories, Chinese Academy of Sciences as a case study, we examine the output results of six image stacking methods: Astrometrica mean and median, and MaxIm DL mean, median, standard deviation (Sigma Clip), and iterative standard deviation (SD Mask). Data reduction is performed on these six output results with specific reference to the Gaia DR2 catalog, and the positional measurement accuracy of stellar images from the six stacking methods is compared. This study reveals anomalies in the positional accuracy of images produced by Astrometrica median stacking. Finally, a methodology for the collaborative use of both software packages in astrometric and sky survey work is proposed.

Full Text

Preamble

Applications and Technology Research for Astrometrica and MaxIm DL in Astrometry

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Abstract: In order to explore the differences in application and CCD image processing between Astrometrica and MaxIm DL in astrometry, this paper provides a detailed comparative and technical study of the two software suites, covering their overall capabilities, CCD image reading/writing and transformation, flat field correction processing, parameter settings, and data reduction and stacking. Using two sets of observational data of the M35 cluster captured by the 1m optical telescope at Yunnan Observatory of the Chinese Academy of Sciences, we investigate the output results of six image stacking methods: Mean and Median from Astrometrica, and Mean, Median, Sigma Clip, and SD Mask from MaxIm DL. Referring to the Gaia DR2 catalog, we perform data reduction on these six output results and compare the positional measurement precision of stellar images. We find anomalies in the positional accuracy of images processed using Astrometrica' s Median stacking. Finally, we propose methods for using the two software suites in combination for astrometric and survey work.

Keywords: Technical Research for Software Used in Astrometry; Astrometry; CCD Image Processing; Astrometrica; MaxIm DL

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1 Introduction

Informatization and industrialization represent trends in societal and technological development. However, current astrometric processing tools and software still lag behind the industrialization standards of traditional manufacturing, leading different researchers to use disparate tools and software in their astrometric processing and research. This approach is not conducive to scientific discussion and exploration to a certain extent. CCD image processing constitutes a crucial step in astrometry, and the correct use of existing astrometric processing tools and software can ensure the accuracy and reliability of CCD image processing results while promoting the advancement of scientific research.

Astrometrica[**?**] and MaxIm DL[**?**] are two publicly available software packages developed for astrometry. Of course, many researchers also use self-developed processing programs and software for astronomical research, such as the radio measurement set file generation software developed by Sun Haomin et al.[**?**] and the one-dimensional spectrum visualization and analysis tool developed by Zhang Shanhu et al.[**?**]. This paper primarily compares and technically investigates the application and processing results of Astrometrica and MaxIm DL in astrometry. Astrometrica, developed by Raab Herbert, is a software for astrometric processing that provides significant assistance and reference value for solar system asteroid surveys and data reduction. Its main functions include CCD image reading/writing and transformation, flat field correction, moving target detection for solar system asteroids, data reduction, and image stacking. The use of Astrometrica has also provided valuable references and achieved good progress in astrometry and survey work. For example, Qiao et al.[?] used Astrometrica to process and measure CCD images of Saturn' s satellites, achieving good accuracy. Vaduvescu et al.[?] employed this software for survey work, discovering 280 near-Earth asteroids. MaxIm DL, developed by Diffraction Limited, is primarily used for astronomical telescope observation, photometry, and astrometry, and is widely utilized by both amateur astronomers and researchers. For instance, Gupta et al.[?] used MaxIm DL for flat field processing and photometric data reduction of OJ 287 observations.

Section 2 of this paper discusses the comparative application and technical research of Astrometrica and MaxIm DL for CCD image processing in astrometry. Section 3 presents experimental comparisons of how six stacking methods from both software packages affect positional measurement precision. Section 4 discusses methods for using Astrometrica and MaxIm DL in combination for astrometry and survey work. The final section provides a summary and proposes directions for future research.

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2 Comparative Application and Technical Research of Astrometrica and MaxIm DL

Astrometrica primarily features CCD image reading/writing and transformation, flat field correction processing, moving target detection for solar system asteroids, data reduction, image stacking, and MPC report generation, providing substantial assistance for solar system survey work and astrometry. MaxIm DL mainly offers functions for controlling observation equipment, reading/writing CCD images, photometry, image quality assessment, image stacking, and running custom scripts. Although MaxIm DL can also perform data reduction, this function requires collaboration with other software, so this paper does not compare the data reduction capabilities of the two software packages. In contrast, MaxIm DL has more functions than Astrometrica, which is expected given their different purchase costs and development scales. This paper primarily compares and technically investigates the functions of the two software packages for astrometric work, specifically detailing CCD image reading/writing and transformation, flat field correction processing, Astrometrica parameter settings and reduction, image stacking, and overall evaluation of both software packages.

2.1 CCD Image Reading/Writing and Transformation

In terms of image reading/writing, Astrometrica can read 8-bit, 16-bit, and 32-bit integer FITS images but can only save them as 16-bit integer images. In comparison, MaxIm DL supports reading and storing more image formats, with details available in the product' s user manual. Notably, neither software currently supports reading 64-bit floating-point FITS images, though SAOImage DS9[?] does support this format. If we need to use Astrometrica and MaxIm

DL for image processing, we should avoid using this image type. Astrometrica, MaxIm DL, and SAOImage DS9 can all view FITS image headers.

However, in practice, we have found that for FITS images with the "Y2K problem" —where header key-value pairs exist in the format "DATE-OBS=MM/DD/YYY" —SAOImage DS9 may display incomplete header information. Additionally, Astrometrica can currently only manually modify observation time header information, whereas MaxIm DL can edit most header information, including adding and deleting key-value pairs.

Both Astrometrica and MaxIm DL can adjust grayscale transformations to improve image visualization. In terms of image transformation capabilities, MaxIm DL is far more powerful than Astrometrica. Beyond simple pixel grayscale adjustments, MaxIm DL supports hot pixel rejection, numerous filters, arbitrary angle rotation, deconvolution, noise addition, pixel binning, and bad pixel removal. When the orientation of captured CCD images does not match the star chart, rotating the image angle can help us manually match stellar images. For astrometric processing, we do not recommend performing image transformation operations other than flat field correction, such as filtering or deconvolution. We believe these operations only improve visual effects without significantly enhancing positional measurement results. Astrometrica' s user manual glossary also states: "Further image processing (such as histogram scaling, filtering, or deconvolution) may distort the centroid and flux of stellar images."

2.2 Flat Field Correction Processing

Flat field correction processing of CCD images is an important step in photometry and is sometimes applied in astrometry. Both Astrometrica and MaxIm DL have flat field correction capabilities. Astrometrica can only use one dark frame and one flat field image for correction processing, while MaxIm DL supports multiple dark, flat, and bias images for correction. Furthermore, MaxIm DL can group different types of calibration images, with each group generating a "Master" image through mean or median methods to save memory space and improve correction speed. MaxIm DL can also custom-adjust the image "Pedestal" pixel value to ensure positive pixel values. When flat-field-processed images need to be used as input for other tools, we generally combine this with MaxIm DL' s Batch Save and Convert function to quickly batch output flat-field-corrected images.

2.3 Astrometrica Parameter Settings and Reduction Methods

In CCD parameter settings, telescope focal length and pixel size can sometimes be difficult to determine as this information may not be included in the image header. This paper presents two methods for determining these parameters. In fact, the ratio of pixel size to telescope focal length is the image scale. We can consider that as long as the ratio between them is correct, Astrometrica can perform correct data reduction and image stacking. The first method to determine image scale is by uploading the image to astrometry.net, with detailed algorithms available in Lang et al.' s paper[?]. The second method involves matching two stars in the image with a star chart and calculating the scale through coordinate transformation relationships.

Using Astrometrica' s data reduction results alone is insufficient for high-precision astrometry. We discuss how to improve the precision of reference stars in Astrometrica' s data reduction. In the software settings, parameters such as reference star search radius, catalog magnitude limits (Upper/Lower Limit), target detection aperture size (Aperture Radius), and detection limit (Detection Limit) all affect reference star precision. The reference star search radius refers to the maximum positional error between searched stars in the image and reference stars in the catalog. When the positional deviation is smaller than the set parameter, the system considers them the same star. Catalog magnitude limit settings affect which reference stars from the catalog are used for matching. We believe adjusting this parameter to the range of bright, unsaturated stars is preferable. The detection aperture size and detection limit have minimal impact on reference star precision when set within the recommended ranges in the user manual. Our practice has found that adjusting the reference star search radius parameter significantly affects reference star precision. We present experimental comparisons using three raw (uncorrected) CCD images of the M35 cluster continuously captured by the 1m optical telescope at Yunnan Observatory of the Chinese Academy of Sciences. We name the three images A, B, and C, using B as the reference to calculate residuals of the same reference stars' two-dimensional coordinates (i.e., the difference between each reference star' s coordinates in A and C and those in B). Figures 1 [Figure 1: see original paper] and 2 [Figure 2: see original paper] show the residual distributions when the reference star search radius is set to 1px and 0.51px, respectively.

From Figure 1, we can see abnormal points in the residual distribution in the Y direction of the image, with several reference stars deviating from normal values by approximately 0.7 pixels. In Figure 2, when we set the reference star search radius to 0.51px (the minimum value the software allows), most abnormal points disappear, and reference star precision improves. We believe the reference star search radius parameter should be set as small as possible to improve reference star measurement precision. Of course, we can also adjust the astrometric limit residual (Astrometric Limit) to select high-precision reference stars for matching. However, it is difficult to determine and set the optimal value for the astrometric limit residual, as it is significantly related to the choice of plate constant order, the number of matched reference stars, and observational data. We also explored the causes of abnormal reference star position residuals. As shown by the abnormal residual points in the lower right subplot of Figure 1, Astrometrica appears to search for the same reference star two or three times, with different stellar center coordinates each time. We indeed found instances in Astrometrica' s data reduction process where the same star was searched as two or three different stars, as shown in Figure 3 [Figure 3: see original paper].

In practice, we have found that Astrometrica may search for faint or large-roundness stellar images as two or three different stars. In other words, Astrometrica is overly sensitive in star detection, which is understandable given its use in survey work. To minimize the impact of this oversensitivity on reference star precision, we recommend setting the reference star search radius to the minimum value of 0.51px.

2.4 CCD Image Stacking

CCD image stacking can improve image signal-to-noise ratio and is greatly beneficial for faint star photometry and positional measurement. Both Astrometrica and MaxIm DL have image stacking capabilities, which we discuss below. In Astrometrica, proper parameter settings and data reduction are prerequisites for image stacking. In stacking parameter settings, target motion speed and angle adjustments are generally used for survey work. For stellar position measurement, these two parameters should be set to 0. Astrometrica offers three stacking methods: Sum, Average, and Median. Typically, the Sum method is suitable for survey work but not for position measurement, as it causes saturation in most stellar images, affecting their quality. Both Average and Median are suitable for position measurement, with detailed comparisons provided in Section 3. By observing Astrometrica' s operation and examining log files, we can understand its image stacking mechanism. First, Astrometrica performs data reduction on two images before stacking. Then, it aligns the images to be stacked (in X and Y axes) based on the data reduction results. However, Astrometrica only considers simple translation in both coordinate directions during image alignment. Finally, Astrometrica performs image stacking according to the set parameters and stacking method.

In MaxIm DL' s stacking process, five steps are performed: image classification, quality-based image selection, image alignment, color adjustment, and stacking method selection. During image classification, MaxIm DL can categorize images based on selected folders, observation targets, and filters used during observation. Additionally, we can perform flat field correction, pixel binning, and other operations before stacking. In the quality-based image selection process, MaxIm DL uses stellar image FWHM, roundness, intensity, and contrast as quality assessment criteria, with detailed descriptions of these parameters available in the software' s user manual. During image alignment, compared to Astrometrica, MaxIm DL' s automatic star alignment mode additionally considers image rotation and scaling relationships, equivalent to considering a 4-constant model. In stacking method selection, besides Sum, Average, and Median methods, MaxIm DL also provides Sigma Clip, SD Mask, and Drizzle stacking methods compared to Astrometrica, with detailed descriptions available in the MaxIm DL user manual. Section 3 of this paper will provide experimental illustrations and detailed discussions of the differences between the stacking methods offered by Astrometrica and MaxIm DL.

3 Comparative Experiment on Image Stacking Methods of Astrometrica and MaxIm DL

In this section, we discuss in detail the impact of stacking methods provided by Astrometrica and MaxIm DL on positional measurement. In our experiments, we did not consider the Sum and Drizzle methods, as Sum stacking causes saturation in many stellar images, while Drizzle stacking is primarily used for undersampled, dithered observations. We compared the Average and Median algorithms provided by Astrometrica with the Average, Median, Sigma Clip, and SD Mask stacking methods provided by MaxIm DL. The Average stacking algorithm aligns a set of images and takes the average of pixel values at each position, while the Median stacking algorithm takes the median of pixel values at each position. The Sigma Clip algorithm performs sigma clipping (the software's recommended value is 3 sigma) on pixel values at each position before taking the average of remaining pixel values, while the SD Mask algorithm is an iterative sigma clipping method (the software' s recommended value is 0.5 sigma with 3 iterations).

We selected CCD images of the M35 cluster captured by the 1m optical telescope at Yunnan Observatory of the Chinese Academy of Sciences for our experiments, including two sets of 50 CCD images observed with an I filter on February 7, 2020, and March 5, 2020, with each image having an exposure time of 60 seconds. These two sets of observations had good atmospheric seeing and minimal image jitter (i.e., basically stable pointing), with most stellar images having FWHM values of 4.5-6 pixels. However, the observations were conducted near full moon, resulting in relatively high sky background values in the images. We will see that image stacking can effectively improve the signal-to-noise ratio of stellar images.

In the processing procedure, first, we used MaxIm DL to perform flat field correction on the two sets of observational data using several flat field and bias images. Second, we used MaxIm DL to perform quality screening on the flat-field-corrected images. For February 7, 2020, the screening criteria were FWHM $\leq$ 5 pixels and roundness $\leq$ 0.2; for March 5, 2020, the criteria were FWHM $\leq$ 6 pixels and roundness $\leq$ 0.2. Third, we selected 15 images meeting quality requirements from each set of observational data, grouping every 5 images together, and performed image stacking using different methods in Astrometrica and MaxIm DL. In MaxIm DL' s stacking operations, other parameters and settings used system defaults or recommended values. The stacked images were then subjected to data reduction with reference to positions from the Gaia DR2 catalog[**?**], following the data reduction method of Lin et al.[**?**]. Figures 4 [Figure 4: see original paper] through 9 [Figure 9: see original paper] show the precision distribution versus magnitude for each stacking method using the February 7 observational data; the precision distribution for the March 5 data was similar.

From Figures 4-9, we can see that the dispersion in declination direction is slightly larger than in right ascension direction. Additionally, we note that images processed using Astrometrica' s Median stacking method (see Figure 5 [Figure 5: see original paper]) show anomalous precision distribution in both right ascension and declination directions—stars brighter than 14th magnitude exhibit worse precision than stars around 14th magnitude, which is an abnormal situation. We believe this anomaly occurs because Astrometrica uses coordinates of stars around 14th magnitude from the overdetermined system of equations for image alignment.

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4 Combined Use of Astrometrica and MaxIm DL

Both Astrometrica and MaxIm DL' s CCD image processing capabilities are significantly helpful for astrometric research, though they consider slightly different functions and details. In positional measurement processing, Qiao et al.[?] performed background adjustment, flat field correction, and data reduction based entirely on Astrometrica. In practice, we can combine the advantages of both software packages for CCD image processing and research. Astrometrica can only use one flat field image and one dark frame for flat field correction, while MaxIm DL can use multiple images for flat field correction. We can first use MaxIm DL for CCD image flat field correction, then use Astrometrica for data reduction on the corrected images. Vaduvescu et al.[?] used Astrometrica for survey work by stacking CCD images using Sum and Median methods, discovering 280 near-Earth asteroids. However, Figure 5 shows that using Astrometrica' s Median stacking results in anomalous positional measurement precision. MaxIm DL considers more parameters and details in image stacking. Furthermore, MaxIm DL does not exhibit anomalous positional measurement precision when performing Median stacking. In practice, we can first use MaxIm DL for CCD image quality screening and stacking, then use Astrometrica for survey work. In summary, combining the use of Astrometrica and MaxIm DL may lead to significant improvements in astrometric and survey work.

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5 Summary and Outlook

This paper introduced the application of Astrometrica and MaxIm DL in astrometry, providing detailed comparisons and technical research on CCD image reading/writing and transformation, flat field correction processing, parameter settings and reduction methods, and image stacking. Additionally, we used two sets of observational data of the M35 cluster captured by the 1m telescope at Yunnan Observatory to compare and investigate the impact of the two software packages' image stacking functions on stellar positional measurement precision. We found that images processed using Astrometrica' s Median stacking exhibit anomalies in positional measurement precision. Based on the characteristics of both software packages, we proposed methods for their combined use. In future research, we will further explore some of MaxIm DL' s image processing functions and apply them to our astrometric work to improve the accuracy and precision of positional measurements.

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Note: Figure translations are in progress. See original paper for figures.