MDia and POTS
The Munich Difference Imaging Analysis for the pre-OmegaTranS Project

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Abstract We describe the Munich Difference Imaging Analysis pipeline that we developed and implemented in the framework of the Astro-WISE\textsuperscript{1} package to automatically measure high precision light curves of a large number of stellar objects using the difference imaging approach. Combined with programs to detect time variability, this software can be used to search for planetary systems or binary stars with the transit method and for variable stars of different kinds. As a first scientific application, we discuss the data reduction and analysis performed with Astro-WISE on the pre-OmegaTranS data set, that we collected during a monitoring campaign of a dense stellar field with the Wide Field Imager at the ESO 2.2 m telescope.

Keywords databases astronomy · extra-solar planets

1 Introduction

The Munich Difference Imaging Analysis Pipeline (MDia) is a software tool to perform high precision photometric measurements in crowded fields such as the Milky Way disk or the bulge of M31. MDia is based on the difference imaging technique proposed by [1] and [2]. Common applications are searches for transiting extra-solar planets, microlensing surveys, stellar rotation and

\textsuperscript{1} Astronomical Wide-field Imaging System for Europe
oscillation studies as well as supernova projects. The MDia tool convolves (degrades) a reference image (constructed from the images collected during the periods of best seeing of the observing campaign, see section 2.2.1) to match the seeing of each single image in the data set. Subtracting the convolved reference image from a single image, one obtains a difference image in which every constant source disappears, while variable objects are visible as positive or negative residuals. PSF-photometry performed on the reference image and on each difference image at the position of the detected sources allows to reconstruct the light curves of each object.

2 The Munich Difference Imaging Analysis Pipeline

2.1 The Algorithm

As proposed by [2], the optimal convolution kernel can be modeled as the superposition of a set of Gaussian kernel base functions which are modulated by a two-dimensional polynomial function in the x- and y-direction:

$$ K(x, y) = \sum_{i=1}^{N} \exp \left[ -\frac{x^2 + y^2}{2\sigma_i^2} \right] \sum_{j=0}^{p_i} \sum_{k=0}^{p_i-j} a_{ijk} x^j y^k. $$

The standard kernel model uses $N=4$ kernel base functions with $\sigma_i = \{0.1, 0.9, 0.6, 0.3\}$ and $p_i = \{0, 2, 4, 6\}$ and a kernel size of 25 x 25 pixel. The total number of coefficients $a_{ijk}$ for this kernel model is 50. Background differences are accounted for using a polynomial model $B(x, y)$.

The coefficients $a_{ijk}$ and the background model are determined simultaneously by $\chi^2$-minimization of the following expression:

$$ \chi^2 = \sum_{x,y} \frac{1}{\sigma^2(x,y)} [(R \otimes K)(x, y) + B(x, y) - S(x, y)]^2, $$

where $R$ is the reference image and $S$ is the single image. Subtracting the convolved image $C := R \otimes K$ from each single image we obtain a difference image $D$:

$$ D(x, y) = \frac{S(x, y) - C(x, y)}{|K|}, $$

with

$$ |K| = \sum_{x,y} K(x, y) $$

being the norm of the kernel. Using this normalization, the difference image
has the same flux level as the reference image. Note that in our implementation we use a normalized kernel (i.e. $|K|=1$) because we photometrically align all images before calculating the kernel (skycalc step, see below). In this case, any variable source could degrade the quality of the kernel. To avoid this, the user can optionally provide a mask that has zero values for each pixel that should be excluded in the determination of the kernel. The implementation of the above equations is described in \[3\].

2.2 The Astro-Wise Implementation

The Astro-WISE tool MDia is designed to operate on a set of regridded images and associated weight images. The regridded images are fully reduced images (bias-subtracted, flatfielded, etc.) that have been resampled to a common target grid with a fixed pixel scale.

In the beginning, the user selects the best seeing images that will be stacked to create a reference image. The second step is to create a difference image for each input regridded image and to create the light curves of all sources detected in the reference image. In the next two sections we describe in detail the steps to create a reference image and to create the light curves.

2.2.1 Creating a Reference Image

We recommend to use 30 input regridded images or more to create a reference image. With this number, masked areas in one image can be replaced with the values of another image with similar PSF. Only if the full data set does not contain 30 good seeing images a lower number might be better because otherwise the input images will have very different PSFs (subby step, see below). For code examples and a complete list of all parameters and their meaning we refer to the MDia manual\[^2\].

In the following we describe the processing steps that are performed to create a reference image:

The first program that is executed is prepare. For each input regridded image it creates an associated error image using the weight image and the read noise value. The error images (which are inverse variance maps) are required by our code to perform a pixel by pixel Gaussian error propagation. In a second step the program wcsmit expands all input regridded images to cover a common area on the sky which contains all pixels of the input images. After that, a polynomial background is fitted and subtracted from the first input image. To do this, the program getsky uses an iterative clipping procedure to mask stars in the fit. In order to subtract the background

\[^2\] http://www.usm.uni-muenchen.de/~koppenh/MDia
in all other images and to ensure that all images have the same flux level, the program skycalc photometrically aligns each input image to the background subtracted first input image. The resulting reference image is a weighted stack of all input regridded images. The program weight calculates a weighting factor for each image based on the background noise and the PSF-FWHM as measured by SExtractor during the ingestion in Astro-WISE. Before stacking, the program subby replaces masked pixels in each input image with the pixel values of the other image which has the most similar PSF. The similarity of the PSFs is determined using a set of isolated stars. If a pixel is masked also in the most similar image, subby replaces with the second most similar image, and so on.

The program usmphot optionally performs PSF-photometry on the reference image in order to measure the fluxes of all sources. These fluxes will be added at a later stage to the fluxes measured in the difference images in order to create the light curves. The program also outputs a PSF image. In another optional step, the program diffima creates a set of kernel base images that are stored and used for difference imaging later.

Figure 1 shows a reference image and the attached error image that is used internally in our code. The reference image was made using 30 input regridded images with ~0.7 arcsec seeing.

2.2.2 Creating the Light Curves

Two inputs are required for the creation of light curves with MDia: A reference image and a set of regridded images. For each input regridded image, a difference image is created. PSF-photometry on the difference image provides high precision measurements of the differential flux of each object. Adding the constant flux of each source as measured in the reference image (see previous section) the light curves are created and stored as ASCII tables. In practice the user splits the input regridded images in subsets of typically 20 images and runs one job per subset. In this way the processing is parallelized making use of a multi-node computer cluster.

Figure 2 shows an example input regridded image together with the difference image created with MDia. Two variable sources are clearly visible as PSF-shaped negative residuals, meaning that the flux in this particular regridded image was lower than in the reference image.

In the following we describe the processing steps that are performed to create light curves with MDia: In the beginning the program wescut expands and/or cuts the input
Fig. 1 Example reference image and its corresponding error image. Due to dithering masked pixels are on different x- and y-positions on the input regridded images and all bad pixel regions (e.g. bad columns) are therefore removed during the stacking process. Nevertheless, bad pixel regions have a larger variance, visible as brighter areas in the error image.

The program skycalc photometrically aligns each image to the reference image, i.e. scales and background corrects each image. The following step is the core of the MDia tool. The program diffima uses the algorithms presented in section 2.1 to produce a difference image for each regridded image. After that, the program curvemaker constructs a PSF for each input image by combining a set of isolated stars in the convolved reference image. These PSFs are then used to perform PSF-photometry on the difference images and subsequently create the light curves which are stored in ASCII format.

2.3 Performance

We study the performance of MDia using a set of 1000 regridded images which have been obtained for the pre-OmegaTranS project (see section 3). We limit the input images may only have integer pixel shifts.
our test to one chip (ccd50) of the ESO Wide Field Imager camera. The size of the images is 2k x 4k pixels. We run our jobs on a Linux cluster which has 68 nodes. Each node is equipped with two 2.6 GHz dual-core AMD Opteron Processors, 6 GByte RAM and 200 GByte local storage. We run only 2 jobs per node because the processing requires a large amount of resources (i.e. memory, I/O and disk space) and running more than two jobs simultaneously on one node turned out to be inefficient.

We execute each job multiple times and give the average execution time in the following. In the first test we create a reference image using 20, 30 and 40 images without creating the kernel base images and without measuring the reference image fluxes. The execution time is 68.5 min, 84.2 min and 144.5 min respectively and therefore roughly 3 min per input image.

Including the creation of the kernel base images costs additional 15.9 min, independent of the number of input images. Turning on PSF-photometry in the reference image costs another 62.3 min. We recommend to include these optional steps when creating a reference image because otherwise both will have to be executed each time the reference image is used in MDia and the overall computation time will be much higher.

In the second step we measure the performance of the MDia task. We use the default kernel model with a kernel size of 25 x 25 pixel and 4 x 8 subfields.
We measure the execution time of several jobs with different number of input regridded images. For each job there is an overhead contribution of 21.0 min which is independent of the number of images (retrieving the kernel base images, creating source lists, storing logfiles, etc.). In addition to this overhead we find that each regridded image needs about 5.7 min. If we split e.g. all 1000 images in subsets of 20, the total execution time of all 50 jobs is 112.5 h with an overhead contribution of 15.6%.

3 The Pre-OmegaTranS Project

In late 2004, a consortium of astronomers from INAF Capodimonte (Italy), Sterrewacht Leiden (Netherlands) and MPE Garching (Germany) designed the OmegaCam Transit Survey (OmegaTranS). A total of 26 nights of guaranteed time observations with OmegaCam [4] at the VLT Survey Telescope [5] were granted to this project by the three institutes. Scaling from existing surveys, OmegaTranS was expected to deliver 10-15 new detections per year. Note that at that time only 8 transiting planets were known.

Due to delays in the construction and commissioning of the telescope, the start of the project was delayed further and further and finally canceled. Instead, we conducted a pre-OmegaTranS survey using the ESO Wide Field Imager (WFI) mounted on the 2.2 m telescope at LaSilla observatory [6].

As the outcome of 7 proposals (both for public ESO time and MPG reserved time), a total of 129 h of observations were collected in the years 2006-2008. Spread over 34 nights we obtained a total of 4433 images of one field, i.e. OTSF-1a, in the Johnson R-band (filter #844, see WFI user manual). The image center of OTSF-1a is at RA=13$^{h}$35$^{m}$41.6$^{s}$ and DEC=−66°42′21″ (2000.0) and the field dimensions are 34′x33′.

The exposure time was 25 s in most cases. Under very good and very bad observing conditions we slightly adjusted the exposure time in order to achieve a stable S/N and to avoid saturating too many stars. The average cycle rate (exposure, readout and file transfer time) was 107 s. 167 images with a seeing larger than 2.5 arcsec were not used because of their bad quality.

In addition to the science images, we obtained calibration images (i.e. bias and flatfield exposures) for each of the 34 nights. The total uncompressed raw data set comprises 725 GBytes (589 GBytes science data, 136 GBytes calibration data).

The basic CCD data reduction steps were done using the Astro-WISE standard calibration pipeline. The steps include bias subtraction, flatfield division, application of a bad pixel map, cosmic ray filtering, astrometric calibration and remapping to a common target pixel grid. For a complete description we refer to the Astro-WISE manual.

Starting with regridded images we used the MDia tool to do high-precision

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Fig. 3 A $\beta$ Lyr type eclipsing binary. This close contact system consists of components with a different surface brightnesses. The light curve is characterized by strong ellipsoidal variations in between two eclipses of unequal depth.

Fig. 4 A non-eclipsing binary contact system with strong ellipsoidal variations at the 10% level. In the pre-OmegaTranS light curve dataset we found $\sim$20 objects of this type.

Fig. 5 A UV Cet type flare star showing a single outburst on May 11th 2007. We extracted the light curves of 16 000 stars. At the bright end we reach an excellent photometric precision of 2-3 mmag which is very close to the theoretically expected precision. Figs. 3 to 5 show a few interesting example light curves from the OmegaTranS data set. The transiting planet candidates are presented in Koppenhoefer et al. (in prep.).
4 Discussion and Conclusions

We described the Munich Difference Imaging Analysis pipeline. After explaining the algorithm we presented the Astro-WISE implementation of MDia. Since a complete description with code examples is beyond the scope of this article we recommend any potential user to further read the MDia manual. In the last section we presented a subset of the results we obtained with the MDia tool on the pre-OmegaTranS data set. We showed some example light curves of variable stars that demonstrate the high precision that can be achieved with the difference imaging technique.

References

1. Tomaney, A.B., Crotts, A.P.S., Expanding the real of microlensing surveys with difference image photometry, AJ, 112, 2872, (1996)
2. Alard, V., Lupton, R.H., A Method for Optimal Image Subtraction, ApJ, 503, 325 (1998)
3. Güssl, C. A., Riffeser, A., Image reduction pipeline for the detection of variable sources in highly crowded field, A&A, 381, 1095, (2002)
4. Kuijken, K., Bender, R., Cappellaro, E., Muschielok, B., Baruffolo, A., Cascone, E., Iwert, O., Mitsch, W., Nicklas, H., Valentijn, E. A., Baade, D., et al., OmegaCAM: the 16k×16k CCD camera for the VLT survey telescope, The Messenger, 110, 15, (2002)
5. Capaccioli, M., Mancini, D., & Sedmak, G., VST: a dedicated wide-field imaging facility at Paranal, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 4836, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, ed. J. A. Tyson & S. Wolff, 43–52, (2002)
6. Baade, D., Meisenheimer, K., Iwert, O., Alonso, J., Augusteijn, T., Beletic, J., Bellemann, H., Benesch, W., Böhm, A., Bönhardt, H., Brewer, J., et al., The Wide Field Imager at the 2.2-m MPG/ESO telescope: first views with a 67-million-facette eye., The Messenger, 95, 15, (1999)