

AUTOCAL: A software application for the calibration of stellar magnitudes

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Abstract. We present a software application that largely automates the process of calibrating stellar magnitudes. AUTOCAL uses a pattern-matching algorithm that Edward Groth and Peter Stetson developed around 1985 to match stars on a FITS frame (using a list of frame coordinates and magnitudes as generated by IRAF) to entries of stars in a catalogue covering the same area of sky. A weighted least squares fitting is performed to calculate a linear function that best describes the relationship between the observed and catalogue magnitudes for these stars. The automation of the matching saves time and decreases the possibility of errors. Additionally, the automated matching can be performed on thousands of stars in a frame, thereby reducing the error margins for the calibrated magnitudes. We present an overview of the software application as well as results obtained for SXP6.85, a Be/X-ray Binary system in the Small Magellanic Cloud. The data were captured with the IRSF telescope located at the South African Astronomical Observatory during three observing runs spanning December 2007 to December 2010. The results are compared to previously published results and show a good agreement.

1. Introduction

The software application discussed here, called AUTOCAL, automates the calibration of stellar magnitudes. The calibration is achieved by comparing the apparent magnitudes of numerous sources in the field of the target to their catalogue magnitudes, and then calculating the linear least squares solution that best describes the relationship between the two sets of magnitude values. The apparent magnitude of the target is then calibrated by applying this linear least squares equation to it.

In order to compare the apparent and catalogue magnitudes of an observed star, AUTOCAL must first identify which star in the catalogue, if any, corresponds to the star in question. The algorithm used to achieve this is a pattern-matching algorithm based on triangle-matching. In essence, the algorithm searches for pairs of similarly shaped triangles, formed by placing stars at their vertices, where one triangle is constructed from the observation data, and the other from the catalogue data. This algorithm was simultaneously developed by Edward Groth [1] and Peter Stetson [2] around 1985.

Although faster and more efficient algorithms to solve the same problem have been developed since, the simplicity and robustness of the algorithm made it preferable for this project. Only a few small adjustments to the algorithm were made during the development of AUTOCAL.

A typical calibration using AUTOCAL can be loosely divided into three sections.

1. Preparation, during which the user provides the input required by AUTOCAL and adjusts the user-defined parameters to suit the dataset that is used.

2. Calibration, which is automated. This includes matching stars from the frame to those listed in the catalogue and all additional tasks required to perform the magnitude calibration.
3. Analysis of the results, during which the user may store the results of the calibration and use the text-based and visual feedback provided by AUTOCAL to ascertain if the calibration went as expected. Furthermore, the user may manipulate the calibration plot (catalogue magnitude vs. instrumental magnitude) in order to improve the fit.

AUTOCAL was used to calculate apparent magnitudes for eight Be/X-ray binary systems in the SMC (Small Magellanic Cloud). The results for SXP6.85 are discussed as an example. Data from three different observation campaigns that searched for variability in a number of such systems in the SMC were used. These campaigns spanned December 2007 to December 2010.

The magnitudes that were calculated using AUTOCAL were compared to magnitudes published in [3] and [5] from the same data and there was good agreement between the results.

2. Calibration using AUTOCAL

The three phases of the calibration procedure, as outlined in the introduction, will be elucidated here.

2.1. Preparation

In this phase the user is required to provide the input necessary for the calibration. Additionally, the user may adjust a number of parameters that affect how the matching of stars is performed. Figure 1 shows the start screen of AUTOCAL, where these steps are performed. Two text files containing the coordinates and magnitudes of the stars that are to be matched, are required. The first is generated from the FITS frame using a standard astronomical software package like IRAF [4] that identifies the positions and calculates instrumental magnitudes for stars on the frame. The coordinates in this file are the pixel coordinates of the FITS frame that correspond to the stars' positions. The second text file is constructed from a catalogue that includes the stars in the field of the FITS frame. AUTOCAL provides an interface that allows star catalogues to be imported into a database that is linked to it. The text file is generated by querying the database through a provided user interface. The coordinates in the second text file are the catalogued RA and Dec values.

The user-provided parameters are used to adjust the automated calibration process for the specific FITS frame that is used. These parameters determine the number of stars from each list used for provisional matching, the minimum separation allowed between stars from the same list before they are discarded, the maximum difference between the coordinates of a star for it to be considered a match and the maximum ratio between the longest and shortest edges of a triangle for it to be used in the provisional matching phase.

Some settings may work better for sparse frames while others may be optimal for densely populated ones. During the testing of AUTOCAL we found that the default parameters worked well for all the frames. Although all the frames had a relatively high star density (as one would expect for the SMC), the number of stars identified per frame varied from 41 to 907, thus indicating that the matching algorithm and its parameters are robust with respect to the density of stars on the FITS frame.

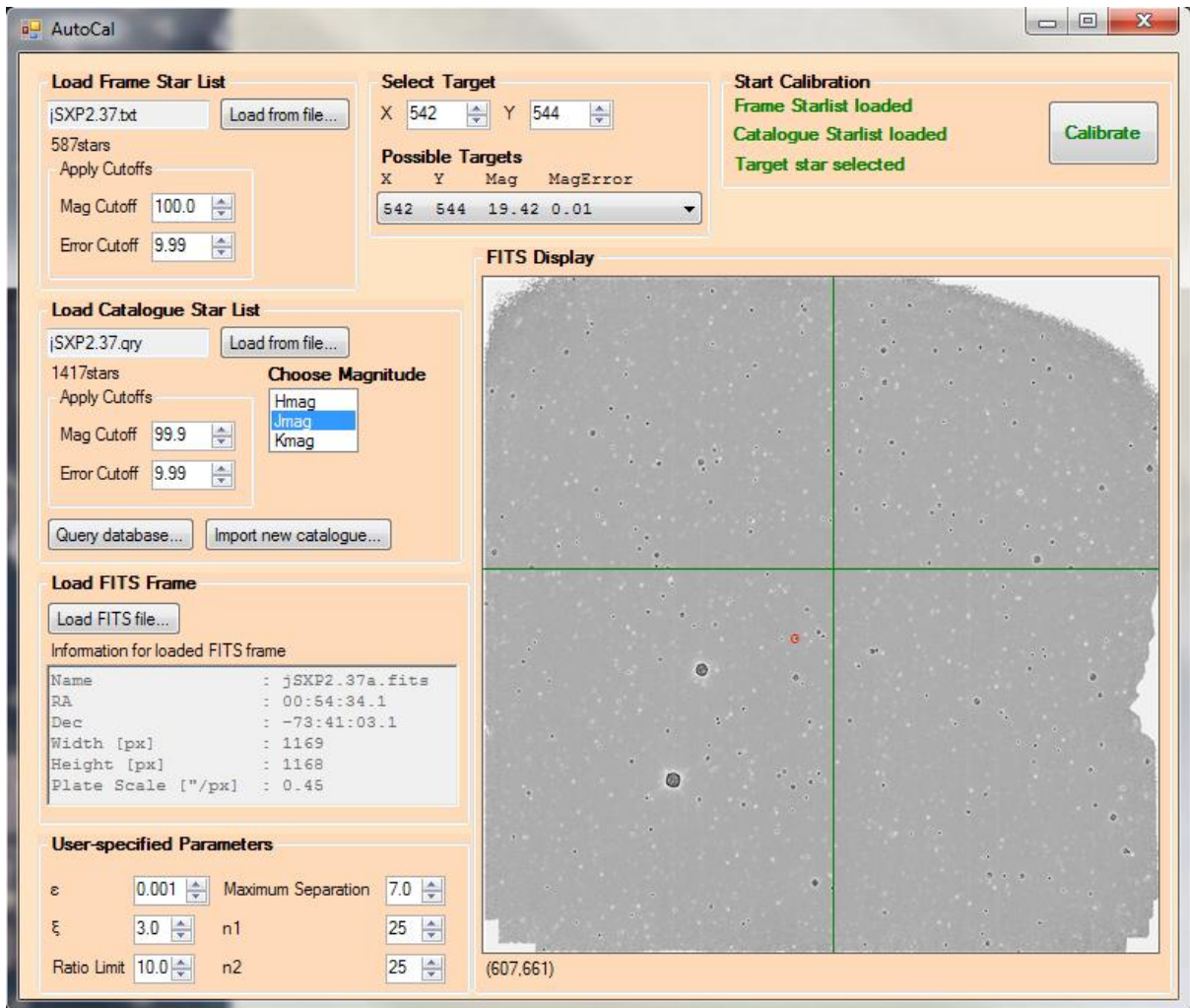


Figure 1. The start screen of AUTOCAL where the user provides input and adjusts the star matching parameters.

2.2. Automated calibration

The calibration procedure is completely automated in AUTOCAL and the software is generally able to match the vast majority of stars on the FITS frame to entries in the catalogue, and to calculate a linear relationship between the two sets of magnitudes, within a second or two. The steps that AUTOCAL follow are listed below. A full discussion of each step is beyond the scope of this document.

1. The target is removed from the list of FITS frame stars and all stars closer to one another than a user-specified threshold are eliminated from both the frame star list and the list of stars from the catalogue to reduce the possibility of incorrect matches being made.
2. The brightest stars from each of the two lists are selected for provisional matching. The number of stars selected from each list is specified by the user.
3. AUTOCAL matches triangles generated from the two lists using the procedure described in detail in [1] and [2]. Stars on corresponding vertices of matched triangles are matched provisionally.
4. The provisionally matched stars are used to transform the coordinate system of the catalogue to that of the FITS frame. The coordinate system of the catalogue is fixed, e.g. it uses equatorial coordinates for J2000.0. The pixel map of the FITS frame is transformed into the catalogue system.

5. With the two lists of stars now using the same coordinate system, entries from the two lists are matched based on their proximity to an entry from the other list.
6. A refined coordinate transformation for the catalogue is now calculated and applied using the larger number of matches found in the previous step.
7. Final matches between entries from the two lists are calculated as in step 5, but using the refined coordinate transformation calculated in step 6.
8. A weight is assigned to each of the matches from step 7, with matches with smaller uncertainties in their magnitudes receiving larger weights. The weights are calculated as $w = (\sigma_{\text{cat}}^2 + \sigma_{\text{ins}}^2)^{-1}$, with σ_{cat} and σ_{ins} denoting the uncertainties in the catalogued and instrumental magnitudes, respectively.
9. A weighted least squares approach, using the weights assigned in the previous step, is used to compute a linear relationship between the catalogue and instrumental (frame) magnitudes of the matched stars.
10. The linear equation calculated in step 9 is applied to the instrumental magnitude of the target, thus calibrating its magnitude to the catalogue. Additionally, the uncertainty in this calibrated magnitude is calculated.

2.3. Post-calibration Analysis

Upon completion of the calibration, the results of the process are displayed. The user can adjust the results by removing matches that are obvious outliers, caused by incorrect matching or faulty magnitude values, and also matches of stars with large magnitudes. Larger magnitudes generally have larger uncertainties and thus smaller weights in the calculation of the linear equation. Often a very good fit can be obtained by using a selection of the brightest matched stars only. An example of the above can be found in the calibration of the magnitudes for SXP6.85, which is discussed in the next section.

Additionally, AUTOCAL allows the user to save an automatically generated summary of the calibration to a text file for further analysis. This summary contains details of every step of the calibration, for instance the number of stars used from each list during the step and the transformation coefficients used for the coordinate transformations.

Once the user is satisfied with the results, the final results can be saved to a text file. This file includes entries for each star that was matched, indicates whether each of these entries were used in the final analysis, and records the equation of the final linear equation as well as the instrumental and calibrated magnitudes of the target. The graph of catalogue magnitudes vs. instrumental magnitudes for the matched stars, from which the linear equation is calculated, can be saved to a bitmap image file.

3. Calibration of magnitudes for SXP6.85 using AUTOCAL

We used AUTOCAL to calibrate magnitudes for SXP6.85 from data captured during three observing campaigns that searched for variability in Be/X-ray binary sources in the SMC. The first campaign took place during December 2007, the second during December 2009 and January 2010 and the third during December 2010. Variability had been reported for SXP6.85 in [3] and [5], both incorporating magnitudes calculated from the same data used here.

The data were captured with the IRSF (InfraRed Survey Facility) telescope at the SAAO's Sutherland observatory using the SIRIUS camera. SIRIUS allows simultaneous exposures to be taken at J (1.25 μm), H (1.65 μm) and K_s (2.15 μm) bands with a field of view of $\sim 7.7 \times 7.7 \text{ arcmin}^2$ [6]. Science frames were constructed using the SIRIUS09 [7] pipeline package that is integrated into IRAF. Standard IRAF/NOAO packages [8] were used to perform PSF photometry on the science frames. The IRSF point source catalogue [9] was used to obtain published magnitude values for the stars on the science frames.

Figure 2 is a plot of catalogue magnitudes vs. instrumental magnitudes for stars that were matched during the calibration of SXP6.85 for an observation done on 18 December 2007 using a J-band filter.

The linear equation calculated by AUTOCAL is displayed in the top-left corner. For this observation the instrumental magnitude of SXP6.85 was 19.60 ± 0.01 and the calibrated magnitude was calculated to be 14.80 ± 0.01 . Blue dots indicate matches that were discarded due to being obvious outliers, representing faint stars or being more than 3σ removed from the final fit.

The results for all three observing campaigns are listed in table 1 along with the results published in [3] and [5]. There is good agreement between the results, with the H-band and K_s -band magnitudes for 18 December 2007 agreeing within the uncertainties specified. There is a slight discrepancy between the results obtained by AUTOCAL and those reported in [3]. The difference is introduced due to the removal of outlining data. If no outlier removal is performed, AUTOCAL calculates a J magnitude of 14.84 ± 0.03 , in agreement with [3]. It is clear from figure 2 that the inclusion of the outliers would skew the fit from the optimal solution.

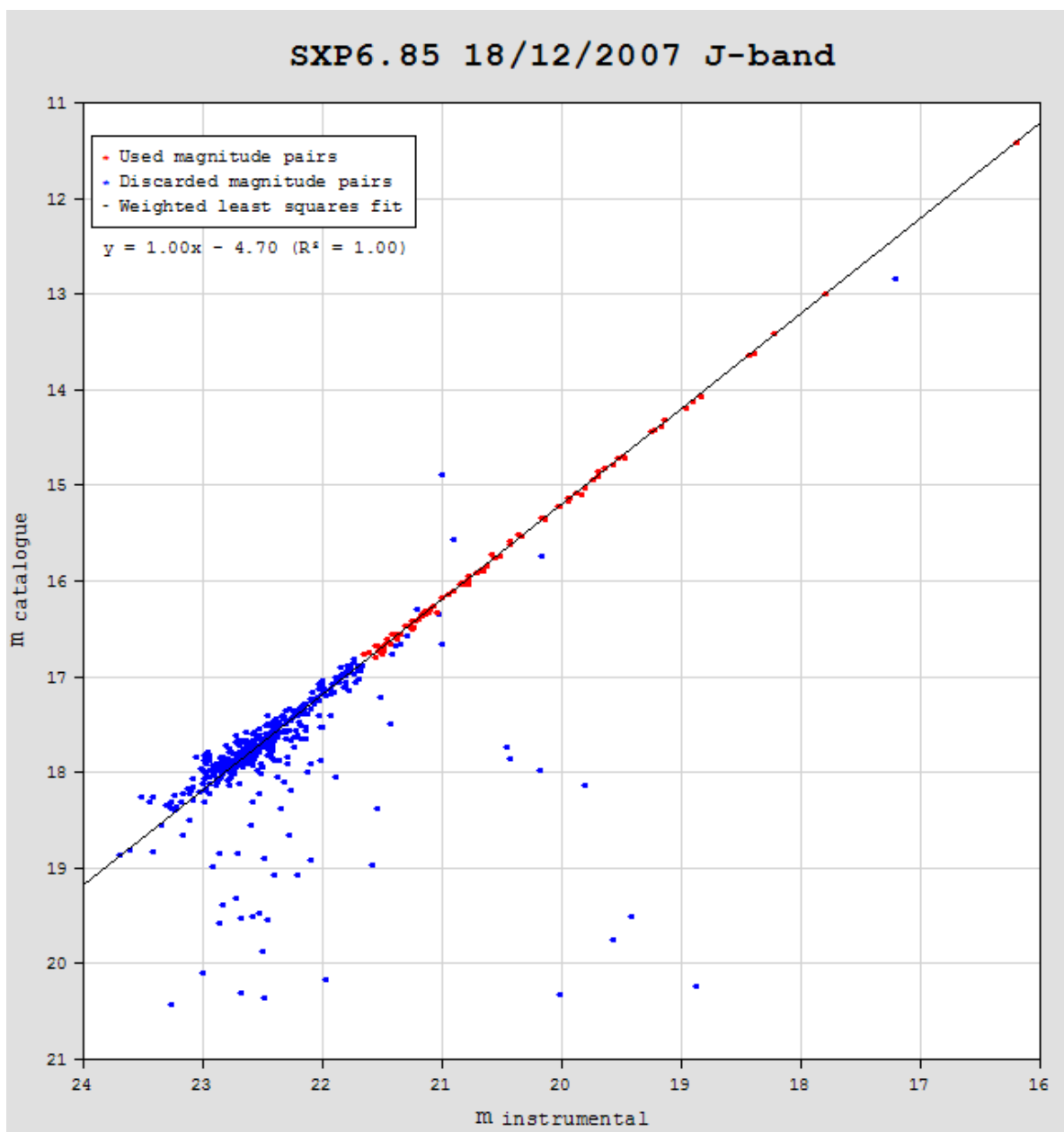


Figure 2. Plot of catalogue magnitudes vs. instrumental magnitudes for stars matched during calibration of SXP6.85, as displayed by AUTOCAL.

Table 1. Calibrated magnitudes calculated for SXP6.85, as calculated by AUTOCAL and published in [3] and [5].

Date	Filter	AUTOCAL	Townsend (2012)
18/12/2007	J	14.80±0.01	14.84±0.02
	H	14.76±0.01	14.77±0.02
	K _s	14.66±0.01	14.67±0.03
30/12/2009	J	14.85±0.01	
	H	14.83±0.01	
	K _s	14.81±0.02	
19/12/2010	J	14.60±0.01	
	H	14.50±0.02	
	K _s	14.37±0.05	

4. Conclusion

AUTOCAL was used to calculate calibrated magnitudes for a Be/X-ray binary system in the SMC and the results agree well with previously published magnitudes calculated from the same data. Generally, AUTOCAL matches a much larger number of stars to a catalogue than those used during a manual calibration. This results in smaller uncertainties in the calibrated magnitudes.

During its testing, which was performed on a total of 55 frames from 8 fields, AUTOCAL was able to calculate calibrated magnitudes for all 55 of the frames.

The advantages of using AUTOCAL over manual calibration include a reduction in the time spent on calibration, elimination of human error and the availability of reports and plots for further analysis. Perhaps the primary advantage of AUTOCAL is its interactive nature, specifically regarding outlier removal. This can lead to more accurate results, as illustrated in section 3.

References

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