Current performance of the CAB robotic telescope: the road to high precision photometry

M. T. Eibe*, L. Cuesta, A. Ullán, A. Pérez-Verde and J. Navas
Centro de Astrobiología, CSIC-INTA, Torrejón de Ardoz, 28850, Madrid, Spain

Abstract. The final limits of the photometric precision that may be achieved with a robotic telescope will depend upon the detection and control of all possible error sources. This involves efforts in mainly three related domains: instrumentation technology, calibration and data treatment. Here we will focus on the optimization of procedures for the automatic reduction of data taken with the 50-cm robotic telescope that is remotely operated at Centro de Astrobiología. The adopted strategies and the photometric precision achieved at different stages of the development of the project will be discussed, highlighting some of the main factors involved in past and future improvements.

Keywords : telescopes – methods: data analysis – techniques: photometric – astrobiology – stars: planetary systems

1. Introduction

The CAB robotic telescope is a 50-cm classical Cassegrain reflector with a focal length of 5 m. It is integrated in a fully remote autonomous observatory so that the acquisition of scientific observations can be carried out in robotic mode without human intervention. Located at the Calar Alto Observatory site in Spain to ensure a large number of usable nights per year, it can be accessed and operated from any other computer connected to the network. More details about the system and about some of the upgrades that have been undertaken during the course of the project can be found in Cuesta et al. (2010) and Ullán et al. (2011). The system is currently running at full performance and actively contributing to long-term photometric monitoring programs. The largest fraction of observing time has been mainly devoted

*email: eibegmt@cab.inta-csic.es
to the follow-up of known planetary systems with the aim of improving orbital parameters estimations. Planetary transit monitoring also allows to investigate possible variations in mid-transit time, depth and/or duration. The telescope time is also planned to be shared between future coordinated program in support of space-based research projects. Apart from continuous monitoring programs, the system is covering more occasional and specific observations that are essential for other scientific projects, such as those being carried out by international networks for the observation and timing of minor planet occultations.

Since the early developing stages of the project, a parallel effort has had to be invested in data management and there has been a clear demand for automated tools to process data. The analysis of experimental data taken during test runs in the first operative phase provided the required feedback to assess performance and make any necessary adjustments in order to improve the instrumental response. The large volumes of data that are generated once the system is working at full performance require fast and reliable procedures to automatically transfer and process the images. This is essential to optimize the efficiency of the whole system in terms of quality of both input data and final outputs.

Understood in this way, the real efficiency may depart from ideal due to several factors. Overall, we can classify them in three main areas:

1. internal sources of error: these are generated after the light beam has entered the telescope system and can be considered as errors of instrumental nature
2. external sources of error: these are generated outside the observatory system, mainly caused by the influence of the atmosphere
3. errors generated as part of the data processing

Many of these factors are interrelated so that their impact on the quality of results cannot be quantified independently. Generally, the first kind of errors need much more attention during the initial development phase of the system because their contribution is much more significant compared to the others. Nevertheless, they all should be subject to periodic monitoring in order to plan in advance the actions needed to keep efficiency at a maximum. Most of instrumental errors and atmospheric effects may be corrected by good maintenance practices as well as calibration procedures. Here we will assume that either the internal or the external sources of error are kept sufficiently low so that the final precision limits of results are significantly determined by uncertainties associated to data processing. Thus we will focus on the third kind of errors mentioned above to emphasize some of the most critical points, considering our instrument and the observational programs that have been carried out so far.
2. Data processing

When it comes to developing tools for the automated processing of data, one has to first consider the characteristics of the input data and the primary scientific objectives. These are the main factors that will determine what are the most suitable techniques and, to some extent, which would be the most useful software, rather than the knowledge and familiarity with specific user programs and applications. The definite choice must be supported by appropriate tests with experimental data and quantitative comparisons with outputs from other tools.

Regarding the main factors that define the type of data, CCD-related parameters are often the most critical. In our experience, they have also been the most subject to change due to equipment upgrades. This should be taken into account when deciding what variables of the reduction code would be fixed and which ones would be defined as configuration options to allow for easy updates. The detector used for the acquisition of most of the data on which this work is based was a 4008×2672 Finger Lakes Instrumentation (FLI) ProLine PL11002M CCD camera. The pixel size is 9 µ, corresponding to a plate scale of 0.37 arcsec per pixel and a field of view of approximately 24×16 arcmin. Considering that the average FWHM (Full-Width Half-Maximum) of the stellar profile due to both seeing and instrumental effects is typically around 2 arcsec, the CCD was used in 2×2 binning mode during the entire observing run. Being the images well sampled (2-3 pixels per average FWHM), the increased binning has the advantage of reducing readout noise, as well as allowing for shorter exposure times, with subsequently shorter time cadences.

The basic layout of the data reduction pipeline is shown in Fig. 1. It consists of three main modules. The first module comprises simple routines running under ESO-MIDAS, which are used to apply standard CCD corrections. Photometry of the corrected images is then performed by the second module. The technique used is differential aperture photometry, which is the most suitable considering the type of data and scientific interests. Aperture photometry is favored against point spread function fitting because the observed fields are small and typically uncrowded, and, on the other hand, the stellar profile is continually changing due to seeing and unstable focus. The small size of the effective field of view has also the advantage that the effect of variations in the optical transmission of the atmosphere can be significantly reduced in the case of differential photometry. Absolute photometry is not needed because the ultimate scientific goal is to precisely determine the relative temporal flux variations from the observational data. The photometry module in the pipeline makes use of the THELI software environment (Erben et al. 2005), which automatically executes the SExtractor code (Bertin & Arnouts 1996) to measure the instrumental magnitudes of the stars. The last stage in the data processing chain deals with the selection of the best stars to be used as comparison and the calculation of differential photometry. This is done by several routines that have been developed in FORTRAN to that specific purpose. More specific details about the methods used in the processing steps can be found in Eibe et al. (2011).
3. Performance evaluation. Key factors affecting photometric precision

In this section we will discuss the most outstanding effects that needed to be checked more carefully because they were found to give rise to larger uncertainties in the final results of the reduction process.

Regarding CCD corrections, there are two main conditions that are essential to efficiently remove the instrumental signature with procedures which are otherwise simple and straightforward. First, it is very important to perform all the tests needed to properly characterize the CCD response for typical working conditions. Empirical estimations of the CCD detector parameters would result in a more realistic determination of errors and would help to detect malfunctions of the system if they are periodically performed. This includes readout noise, gain, linearity or shutter correction effects (Fig. 2), specially if short exposure times may be used, as is often the case with flat-field frames. Secondly, the noise introduced at this stage should be kept at a minimum by using master calibration images with a high signal-to-noise ratio.

Performance of the photometry is conditioned by the choice of optimal configuration parameters for the execution of SExtractor. It is beyond the scope of this contributed talk to examine in detail the impact of each individual parameter. The performance of SExtractor is more extensively discussed in Bertin & Arnouts (1996). It is important to carry out experiments with different data sets in order to assess a standard level of performance, as well as to define indicators that allow to identify significant deviations from that standard performance. Likewise, it is always helpful to inspect the specific fields of view that are going to be observed in order to check in advance whether there are any special features that may cause the software to produce worse results (well isolated sources, range of stellar brightness, light pollution). Among all the input parameters, the aperture size is extremely important in case of fixed aperture photometry because it may lead to large errors. If optimum, however, it will be less sensitive to small changes. In fact, SExtractor has the advantage that it
The shutter map obtained for the FLI PL-11002 CCD camera attached to the CAB telescope.

allows to scale and model the aperture shape to account for profile variations that are reasonably small. The choice of the right aperture size is based on diagnostics of the profile sampling and the so-called growth curves (Stetson P. B. 1990). Fig. 3 shows an example of the growth curves that were generated for several images of the same night and for the specific stars that were finally used for differential photometry. It is seen that the behavior is very similar for the different stars and for the different images. Based on this, one should not expect a large dispersion in the final light curves due to the selection of aperture size. It is important that the stars of interest have all similar relative brightness. Otherwise, the individual growth curves may be too different so that using the same aperture size for all the stars may lead to significant internal errors.

One of the factors that needs to be frequently monitored is the range of variation of the extracted sources in pixel position along the time series. This was often decisive for achieving a permanent high level of precision during the different periods of activity in the history of the project. Fig. 4 shows the drift of the telescope in x and y pixel position during one of the time series for which the final photometric precision was around 4 mmag. Variations are more smooth beyond the series number 65, with an average scatter of 8 pixels over a period of approximately 1.5 h at pointing positions that are between 30 and 70 degrees altitude.

In our system, this shift is conditioned mostly by the tracking performance. Because the tracking mechanism relies on a good pointing model, it is important to identify those pointing positions for which the associated uncertainty is larger, as well as to periodically check if the model needs to be updated. Although the tracking per-
Figure 3. Growth curves for aperture size diagnostics. Each of the individual plots shows the family of growth curves for the stars of interest in a given image.

formance would be among the class of internal sources of error that was established in Section 1, it must be noted that the final impact of this effect on photometric precision will depend on the scale of spatial errors in the flat-field frame. This is an example of how the different kinds of factors affecting the quality of outputs may be interrelated.

Finally, the cost in final precision due to errors that originate during computation of the differential photometry may also be high. While having a small field of view helps to simplify the treatment of corrections for atmospheric extinction effects, it may be a disadvantage for the automatic selection of stars that are suitable for comparison, due to the reduced number of possibilities. Care must be taken that the selected final stars have similar relative brightness and colors, specially when one tries to estimate separately the contributions of different sources of error. Including stars that differ too much in relative brightness and/or colors may introduce errors as said above, in which case it would be necessary to apply additional corrections as part of the process. But if the initial sample of candidates for comparison is small and it is not known a priory whether constant stars are dominant over variable stars in that sample, then a simple rejection based on the standard deviation of the normalized flux with respect to the total average may not be reliable. These are simple questions that might be overlooked when applying to small fields the same automatic procedures that are normally run on larger fields. This and, in general, the overall performance of the code when comput-
Current performance of the CAB robotic telescope

Figure 4. Variation of the x (red) and y (black) pixel position of the target star with time.ing the statistics in order to evaluate possible reference stars, was notably improved
after two main upgrades of the initial version. First, an indicator of image quality was
introduced and, secondly, the statistical evaluation of temporal variability of compar-
ison stars was done in a more iterative process. The approach consists in first defining
a sub-sample of images having high signal-to-noise ratio and similar relative photometric zero point. These are used to calculate average instrumental magnitudes for all
the stars marked as candidate comparison stars, which give a measure of the expected
values for the best instrumental response. Differential magnitudes with respect to
their respective averages are then computed for all the candidates and all the images,
resulting in a time series of instrumental magnitude deviations. For good reference
stars, the magnitude deviations calculated in this way would mainly reflect the vari-
ation of the relative photometric zero point of individual images, so that, for a given
image, they should all have a narrow distribution around a mean value. Stars with
significant variability, however, would behave less consistently, with systematically
higher deviations than the rest of stars in the selected sample. Besides improving the
statistics, this method helps to assess whether the variations seen in the final light
curve are uniquely associated with the target star measurement or may originate from
deviations in the reference stars that propagate through the calculation of differential
photometry.

4. Future and conclusions

We have presented some of the latest results obtained with the INTA-CAB 50-cm
robotic telescope to illustrate the effect of major upgrades made in the last two years,
with respect to previous stages of development. Advances made in the instrumental
equipment, system calibration and methods have allowed to achieve the dual purpose
of improving the whole system performance in robotic mode and pushing the limits
of precision to the level of millimagnitudes (currently 2-3 millimagnitudes for stellar magnitudes around $V = 10$ mag).

Improvements are currently being made to generate more real-time quality controls as part of the data reduction. This will help to monitor the performance of the overall system in a more automatic way, enabling better planning of actions and readjustments needed for optimum data quality. On the other hand, the establishment of more efficient programs of preventive maintenance will be essential in order to keep the quality of outputs over longer periods of time. Additional efforts are also needed to produce other diagnostic tests that may contribute to a better knowledge of the system, such as the study of atmospheric extinction or scattering light. Future plans include the extension of the current follow-up photometric programs of extrasolar transiting planets to other variable systems and the increase of the current capabilities of the system for multi-wavelength observations.

Acknowledgments

The authors would like to acknowledge financial support from the INTA budget for Astrobiology up to the year 2009, and the Spanish programme AYA2009-14000-C03-02 starting in 2010. The authors are also grateful to engineering staff from Calar Alto Observatory for having kindly provided assistance to remedy operational failures in the observatory system.

References

Erben T., Schirmer M., Dietrich J. P., et al., 2005, Astronomische Nachrichten, 326, 6, 432