Mem. S.A.It. Vol. 74, 884

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The Carina Project: Absolute and Relative Calibrations

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Abstract. We discuss the reduction strategy adopted to perform the relative and the absolute calibration of the Wide Field Imager (WFI) available at the 2.2m ESO/MPI telescope and of the Mosaic Camera (MC) available at the 4m CTIO Blanco telescope. To properly constrain the occurrence of deceptive systematic errors in the relative calibration we observed with each chip the same set of stars. Current photometry seems to suggest that the WFI shows a positional effect when moving from the top to the bottom of individual chips. Preliminary results based on an independent data set collected with the MC suggest that this camera is only marginally affected by the same problem. To perform the absolute calibration we observed with each chip the same set of standard stars. The sample covers a wide color range and the accuracy both in the B and in the V-band appears to be of the order of a few hundredths of magnitude. Finally, we briefly outline the observing strategy to improve both relative and absolute calibrations of mosaic CCD cameras.

Key words. Galaxies: individual (Carina) – Local Group – Stars: i evolution – Stars: Image processing – Stars: oscillations

1. Introduction

During the last twenty years the use of CCD cameras played a crucial role in the improvement of the photometric accuracy

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of both extended and point sources. This and the increase in the spatial resolution (ACS@HST, pixel scale$\approx$ 0.05 arcsec) provided the unique opportunity to perform accurate photometry of faint sources even in crowded stellar fields such as the innermost regions of globular clusters. One of the few limits of these detectors has been the relatively small field of view (FOV). However, during the last few years the advent of wide field imagers brought forward the opportunity to collect homogeneous and accurate photometric data over large sky areas. The new mosaic cameras present a FOV that is approximately 30×30 arcmin and are available at telescopes of the 2-4m class (2.2m ESO/MPI, 4m CTIO Blanco, 4m CFHT) and of the 8m class (Subaru, LBT). These new instruments are fundamental to address a broad range of astrophysical problems ranging from the detection of Near Earth Objects (NEOs) to the detection and characterization of Active Galactic Nuclei (AGNs) and Supernovae (Bono et al. 2003, these proceedings). They are crucial to properly address several stellar astrophysics issues such as microlensing events (MACHO, EROS, OGLE) and stellar populations over extended sky regions, including the halo and bulge of the Galaxy, the outermost regions of globular clusters, and Local Group (LG) dwarf galaxies (Held et al. 2001; Dall'Ora et al. 2003; Monelli et al. 2003a).

Although the wide field imagers present several undoubted advantages when compared with previous detectors, they also bring forward several thorny problems in case we are interested in accurate photometric measurements. A key point, quite often neglected, is that mosaic cameras are an ensemble of instruments, and therefore the pre-reduction as well as absolute and relative calibrations need to be carefully addressed (Manfroid & Selman 2001). A few years ago we began an ambitious project aimed at investigating on a star-by-star basis the stellar content of both globular clusters and LG spheroidal galaxies. The main aim of this project is to supply accurate and homogeneous photometry for both static and variable stars from the tip of the Red Giant Branch (RGB) down to the Main Sequence Turn-Off (MSTO). To properly accomplish this project we need to collect multi-band time series data that cover a large time interval. This requirement is mandatory not only to properly detect and measure long-period variables, but also to overcome aliases in the variability detection.
In the following we discuss the reduction strategy we adopted to perform the photometry for the Carina Project on two different sets of B,V time series data collected with the WFI available at the 2.2m ESO/MPI telescope and with the MC available at the 4m CTIO Blanco telescope.

2. Relative and Absolute Calibration: WFI Data Set

The data set we have collected for the Carina project with the WFI available at the 2.2m ESO/MPI telescope have already been discussed by Dall'Ora et al. (2003, these proceedings) and by Monelli et al. (2003a). In particular, raw images have been pre-processed, i.e. bias subtraction and flat fielding, using the NOAO *mscred* (Valdes 1997) tasks available in the IRAF data analysis environment. In the following we address in detail the absolute and the relative calibration of these data. The reason why we are interested in providing accurate relative calibrations of individual chips is twofold. *i)* The occurrence of positional effects, even at the level of a few hundredths of magnitude, might cause a spurious color broadening of key evolutionary features such as the RGB and the MSTO. This means that the slope and the width in color of the RGB need to be cautiously treated to estimate the spread in metallicity. The same outcome applies to the spread in stellar ages. *ii)* The same problem might also affect not only the mean magnitude of variable stars but also the shape of their light curves. The reason why we are interested in providing accurate absolute cali-

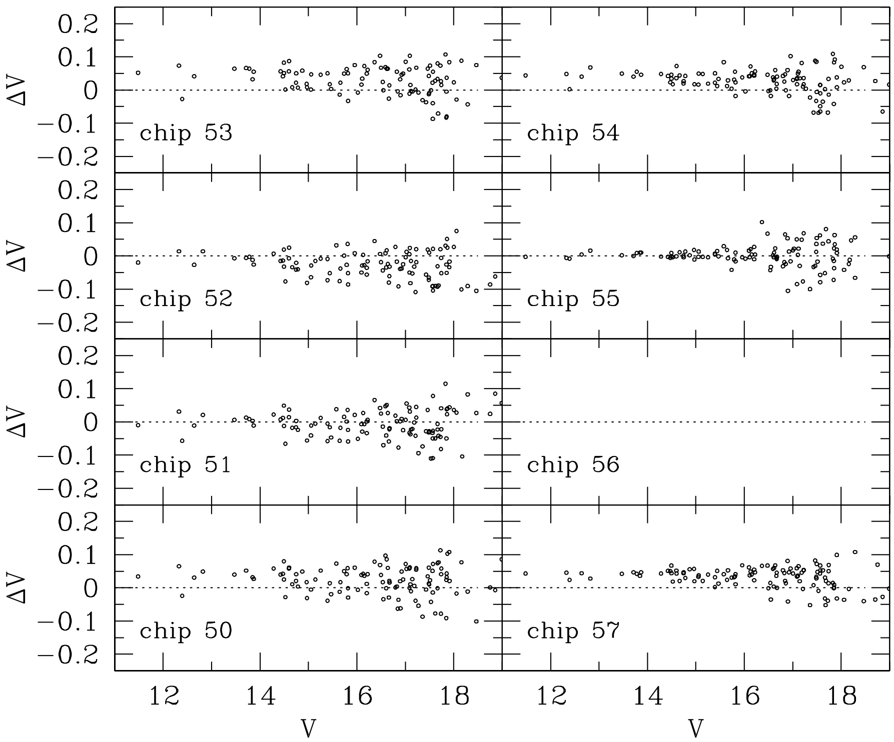

Fig. 1. Difference in the instrumental V magnitude (WFI) for the same stars as a function of the V magnitude measured between the reference chip # 56 and the other chips. Data plotted in the left chips #50-53, display an unexpected large scatter in the residuals, even for bright stars. This suggests a dependence of the residuals on the star position inside the mosaic.

brations of individual chips is twofold. *i)* The plausibility of the comparison between theory and observations relies on the accuracy of the absolute photometric zero-point in individual bands. This is a fundamental requirement for the distance modulus, and in turn for the absolute ages. *ii)* The occurrence of a systematic error in the absolute zero-point or the fact that standard stars cover a limited color range might also introduce, via the color term, a drift in the magnitude of stars when moving from the red to the blue region of the CMD. Keeping in mind these problems we decided to investigate in detail the relative and the absolute calibration of WFI data.

Figure 1 shows the difference in the V magnitude between the same standard stars of the Landolt field Rubin 149, measured on the chip #56 taken as reference and on the other seven chips. The residuals plotted in the left panels show a large intrinsic spread even for stars brighter than $V \approx 16.5$ mag, while data plotted in the right panel show the typical distribution expected for a steady decrease in the SN ratio for increasing magnitudes. Oddly enough, we found that the difference in the behavior between left and right panels is reversed if we adopt as a reference the chip #51. We performed the same test using B-band measurements and we found the same trend, but slightly smaller than in the V-band. These are the first evidence that current photometric data could be affected by an additional deceptive error.

We performed several experiments and eventually we found that the intrinsic spread depends on the position of the star inside the chip. In particular, we found that it depends on the position along the Y-axis, while along the X-axis the effect is vanishing. Figure 2 shows the difference in the instrumental V magnitude between the measurement performed with the chip #56 and with the other chips as a function of the Y coordinate. Note that to increase the size of the sample we used all the stars with high signal to noise ratio located inside the standard field Rubin 149, i.e. standard and nonstandard stars. Data plotted in the left panels show that the V magnitude of the same stars is affected by an uncertainty that is vanishing for $Y \approx 2000$ and becomes of the order of $\approx \pm 0.07$ mag close to the bottom or the top of the chip. A cubic fit as a function of the Y coordinate appears a good representation of current residuals. The positional effect is, as expected, smaller amongst the right chips. In particular, it is of the order of a few thousandths of magnitude for the chip # 55, while a linear relation properly fits the residuals of the external chips # 54 and # 57. To investigate whether the positional effect does depend on the photometric band, we performed the same test but using the B-band data. Interestingly enough, data plotted in Figure 3 show the same behavior of the V-band but the effect is smaller in the B than in the V-band. This finding supports the evidence that the positional effect depends on the wavelength, and thus explains why we see the effect in B-V. As a final step we accomplished the absolute calibration of the reference chip # 56 only using the standard stars of the Rubin 149 field (see Figure 4). Note that for this chip we simultaneously applied the positional correction and the transformation from instrumental into B and V Johnson magnitudes.

Unfortunately, the current set of standard stars located inside the chip # 56 only cover a limited region that ranges from $Y \approx 600$ px to $Y \approx 2500$ px. Moreover and even more importantly, we plan to use WFI data that have been collected over a large time interval, therefore we are also interested in testing whether the positional effect presents a systematic drift as a function of time. Fortunately enough, we found that in the ESO Science Archive are available a set of B,V data collected with the WFI and centered on the globular cluster 47 Tuc. For this cluster are available a large set of standard stars measured by Stetson (2000[1]). Therefore to properly address previous possible problems we applied the quoted corrections for the positional effect to Stetson's standards located inside the reference chip # 56. Figure 5 shows that the new sample of standard stars present the same behavior and that current correction (dashed line) overestimates by approximately 0.01-0.02 mag the positional effect for $2600 \leq Y \leq 3600$ px. At present we cannot firmly assess whether this discrepancy is real; more accurate and uniformly distributed standard stars are necessary to establish on a quantitative basis this effect.

In this context it is worth mentioning that the positional effect marginally depends on the approach adopted to pre-process raw data. As a matter of fact, we performed several tests using the same set of B,V images centered on 47 Tuc collected with the WFI (ESO Science Archive). These data have been pre-processed by using super-flats, dome-flats, as well as sky-flats and we found that the positional effect, within current uncertainties, is marginally affected by the pre-reduction strategy. Once the posi-

[1] See also the web page http://cadcwww.hia.nrc.ca/standards

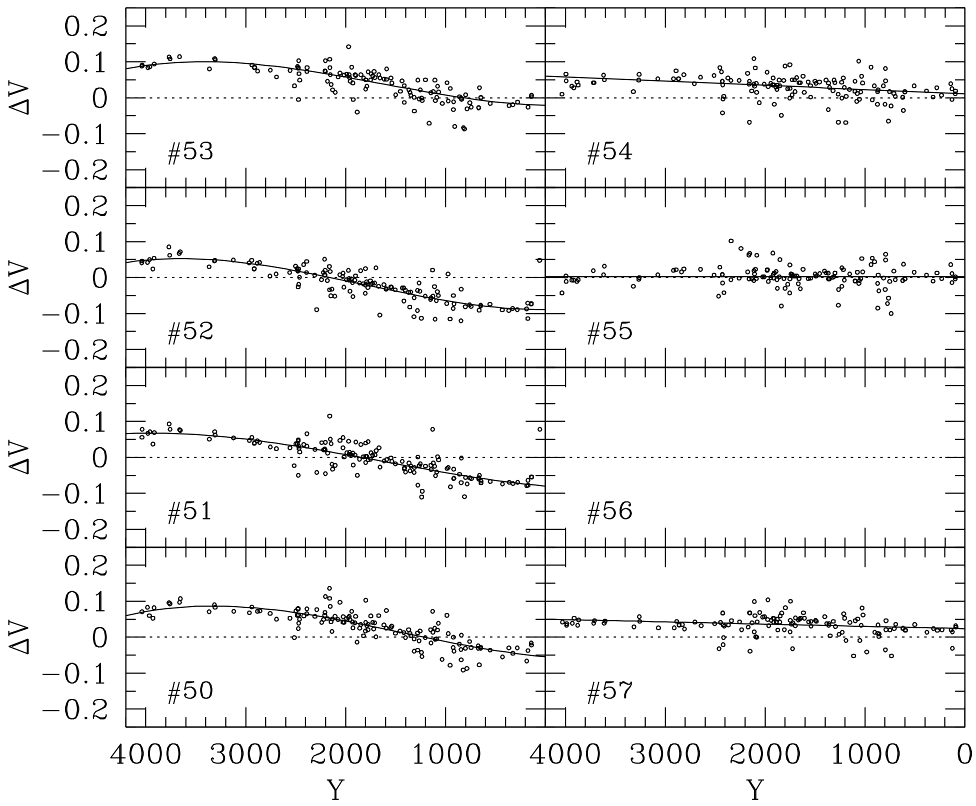

Fig. 2. Difference in the instrumental V magnitude (WFI) between the measurement of the same stars in the reference chip # 56 and in the other chips. The solid lines show the linear (right) or the cubic (left) relations we estimated to remove the positional effect.

tional effect was removed, the absolute calibration of the other chips was performed using the following procedure:

i) To improve the color range covered by standard stars and to properly estimate the extinction coefficients we also included other standard fields (PG 0918, PG 1323, PG 1633) that have been observed at different air masses together with the Carina dSph and that were available in the ESO Science/Archive (Monelli et al. 2003a). We adopted a large fraction of the Stetson standard stars brighter than $V \approx 19$ mag located in these four Landolt fields. The sample includes 117 stars and the $B - V$ color ranges from -0.2 to 1.4 mag. Once the positional effect has been removed we estimated the transformations into the Johnson system.

ii) On the basis of the scientific frames collected during the same nights of the standard fields, we selected more than 60 bright and isolated stars per chip. The aperture photometry of these stars was corrected for

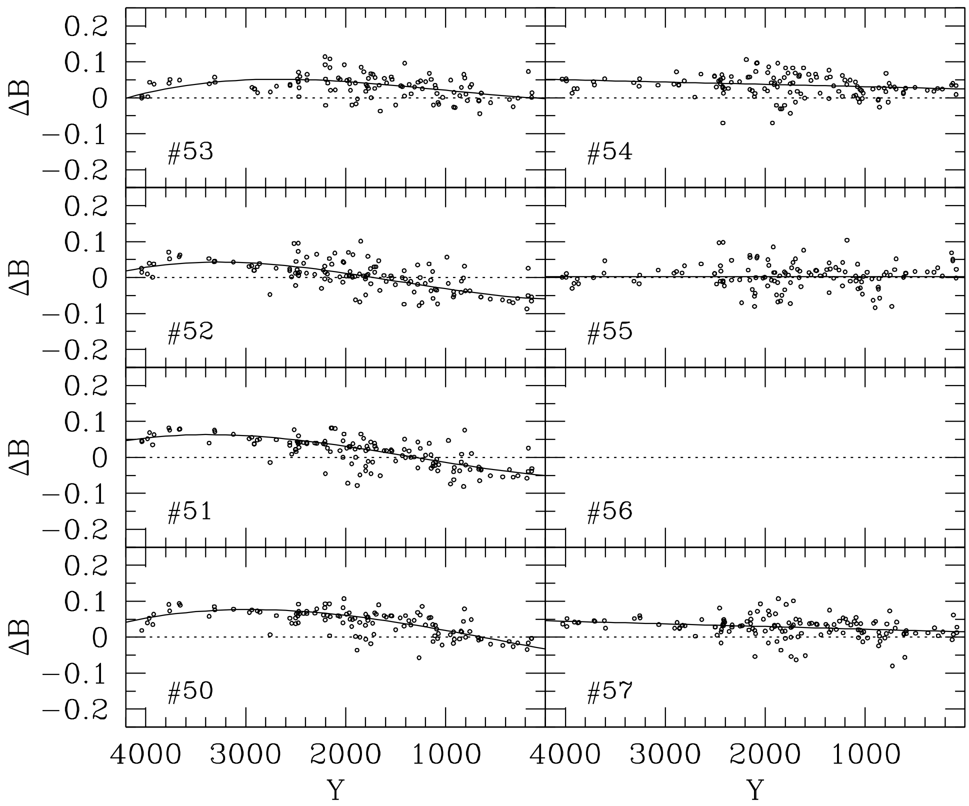

Fig. 3. Same as Figure 2, but for the B-band. Note that the residuals, both in the left and in the right chips, are smaller than in the V-band.

the positional effect of individual chips, and then transformed into the Johnson system using the quoted transformations (see *i)*).

iii) The eight subsamples of secondary standard stars were adopted to estimate the color equations, and in turn to calibrate the photometry of individual chips (see the Castellani et al. 2003). We adopted this strategy because the transformation of the instrumental B magnitudes into the Johnson system disclosed a large coefficient in the color term, i.e. 0.456 ± 0.016. Therefore the use of a unique set of color equations for the entire mosaic might introduce systematic uncertainties.

3. Relative and Absolute Calibration: Mosaic Camera Data Set

The data set we have collected for the Carina project with the Mosaic Camera (MC) available at the 4m CTIO Blanco telescope have already been discussed by Monelli et al. (2003b, these proceedings). In the following we discuss a new independent absolute and relative calibration of these

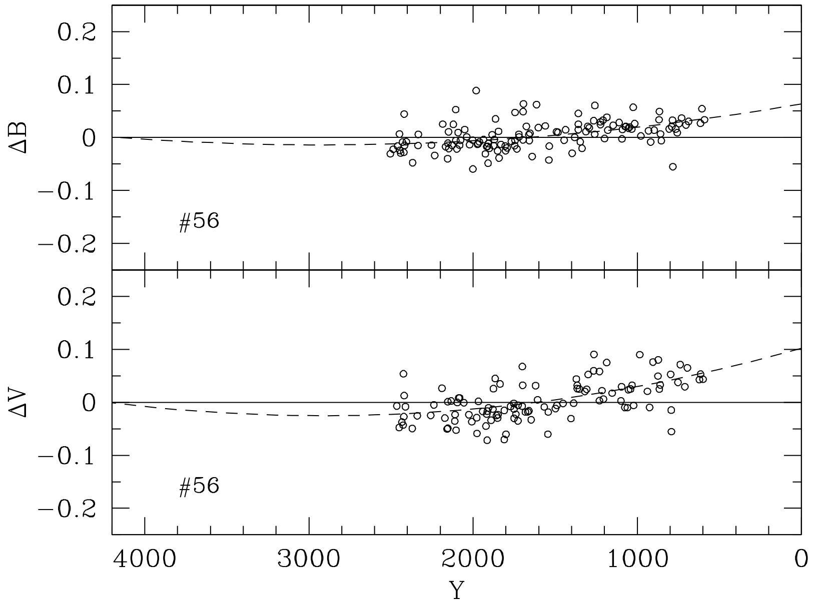

Fig. 4. Difference between current B,V instrumental magnitudes (WFI) and B (top) and V (bottom) Johnson standard magnitudes collected by Stetson (2000) in the Rubin 149 standard field. The dashed line shows the quadratic fit we estimated to remove the positional effect.

data. The reader interested in a more detailed discussion concerning the observing and the reduction strategies is referred to Monelli et al. (2003c, in preparation). The reason why we are interested in new relative and absolute calibrations of the Carina dSph is twofold.
i) We adopted the photometry of the WFI to calibrate the data collected with the MC (Monelli et al. 2003b). However, we found a positional effect in the WFI data that was removed at the level of a few hundredths of magnitude. Moreover, the B-band filter of the WFI was changed soon after we collected the first set of time series data. This means that for the new B,V data set that we collected with this instrument we need to perform once again both the relative and the absolute calibration.
ii) The photometry collected both with the 2.2m ESO/MPI and with the 4m CTIO telescopes disclosed the occurrence of a blue plume of stars located at $B - V \approx -0.1$. According to current photometry it is not clear whether they are young MS stars or blue Horizontal Branch (HB) stars. To properly investigate the nature of these objects we need an accurate color calibration across the CMD.

To overcome these problems, we decided to collect a new independent set of standard stars with the MC. The new data were col-

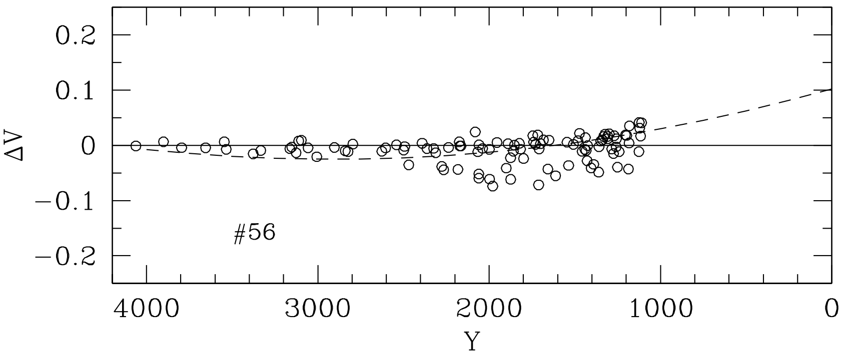

Fig. 5. Difference between V instrumental magnitudes (WFI) and V Johnson standard magnitudes collected by Stetson (2000) in 47 Tuc. The dashed line shows the quadratic fit adopted to remove the positional effect of the standard stars in the Rubin 149 standard field (see Figure 4).

lected on December 31 2002, and the same standard field SA 98 was observed with all the chips of this CCD camera. We ended up with a sample of at least 150 standard stars per chip brighter than $V \approx 18$ mag, and B-V colors ranging from 0.0 to 2.2 mag.

Figure 6 shows the difference in the instrumental V magnitude as a function of the V magnitude. Data plotted in these panels show that the positional effect in the MC, if present, is quite small. The same outcome applies for the B-band. However, data plotted in the bottom right chip show an intrinsic dispersion as a function of the magnitude reminiscent of the behavior we found in WFI data. Preliminary findings suggest that the positional effect, in this chip is, in contrast with the WFI, along the X-axis (short) instead of the Y-axis (long). The absolute calibration will be performed once we have removed this subtle effect.

4. Conclusions and Future perspectives

Recent findings based on photometric data collected with the WFI available at the 2.2m ESO/MPI telescope indicate that the 8 CCD chips could be affected by positional effects involving zero-point errors of the order of several hundredths of magnitude. A similar result was also found by Navasardyan et al. (2002, private communication). This unpleasant effect could be due to spurious scattered light in the camera (Anderson et al. 1995), to which the focal reducer type of optical arrangement used with WFI is unfortunately rather subject. The MC, a prime focus instrument, has a very different type of optical corrector that is not known to exhibit such effects. The marginal effect seen in a single MC CCD may possibly be related to a CCD problem (charge transfer?) rather than an optical problem.

In this context it is worth mentioning that the procedure we devised to estimate the zero-point correction map is quite similar to the Photometric Super-Flat (PSF) discussed by Manfroid & Selman (2001). We did not perform a detailed comparison between the two different approaches but the two methods do have several substantial differences. i) To apply the PSF method it is necessary to collect the scientific data with a special dithering. This means that it cannot be applied to archive data. Our method relies on the observations of standard stars and once the correction map has been estimated it can be easily applied to

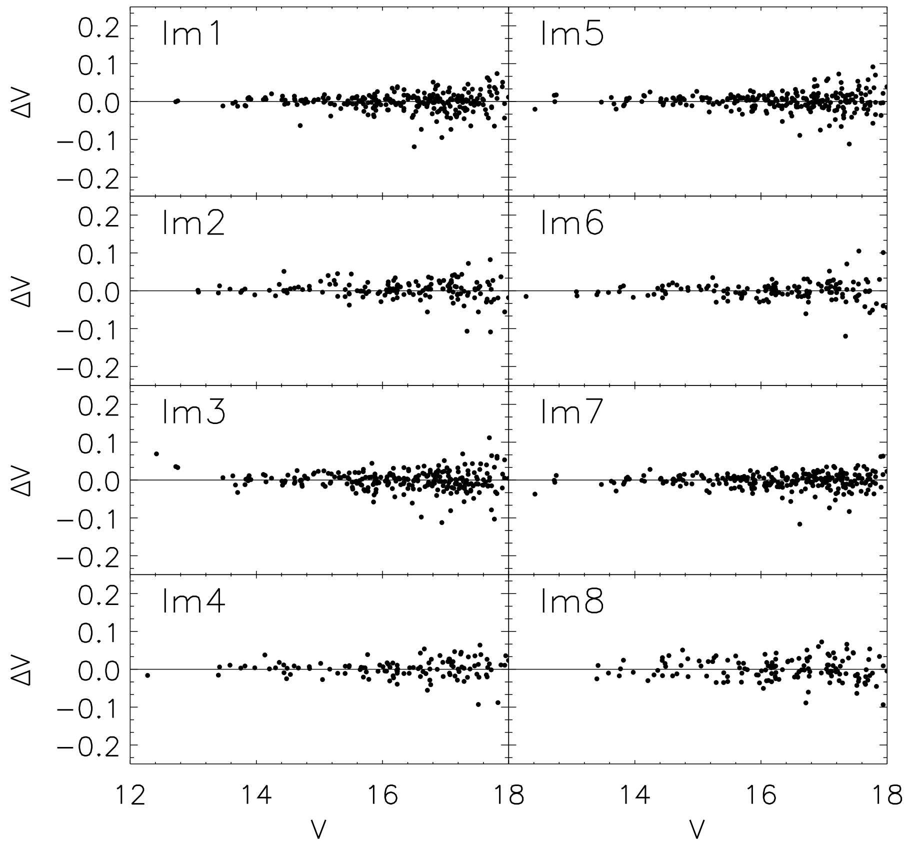

Fig. 6. Difference in the instrumental V magnitude (MC) for the same standard stars (SA 98) as a function of the V magnitude. See text for more details.

old and new data collected with the WFI. This working hypothesis applies if the preliminary evidence that the relative calibration does not change with time is confirmed by new tests. ii) Our method does not require the inversion of any matrix to derive the zero-point of the correction map. This means that it does not depend on the dithering adopted to collect scientific images.

The current results disclose the feasibility of accurate photometry with wide field imagers. However, multiband accurate and homogeneous data of the same standard stellar fields are required to properly calibrate these fundamental instruments. The content of the previous sentence might appear obvious, but it is not. The use of wide field imagers introduced new challenging problems concerning the calibrations. The Landolt standard fields only cover limited sky areas and the number of standard stars is quite limited. Therefore, the calibration of wide field imagers does require a nontrivial amount of telescope time during photometric nights. To overcome these difficulties Stetson (2000) undertook a paramount observational effort to increase both the field of view and the sample of standard stars in classical Landolt fields.

Obviously the use of standard fields to perform both relative and absolute calibrations is one of the most popular approaches to perform both relative and absolute calibrations. It goes without saying that the opportunity to have a sizable sample of standard stars inside the field of view of the scientific images would imply a substantial improvement not only in the photometric accuracy but also a more efficient use of telescope time. This requirement is mandatory in stellar photometry of stellar systems such as globular clusters and dwarf galaxies, but is also very useful for the calibrations of wide field imagers. In fact, the use of stellar systems as standard stellar fields presents several key advantages when compared with classical ones. In particular, *i)* several globular clusters and dwarf galaxies cover a sky area that ranges from 0.5 to 1 square degree. This means that in one single exposure a sizable sample of standard stars could be collected in each individual chip. Moreover, they are visible all over the year. *ii)* Stellar populations in these stellar systems cover a wide color range at relatively bright magnitudes. They only present one major problem: the innermost regions, typically a few arcmin, are affected by crowding problems, but *ad hoc* dithering procedures can be devised to overcome this problem. Fortunately enough, Stetson (2000) already collected large sample of standard stars in in a large sample of stellar systems, and this is an ongoing fundamental project. This means that in the near future relative and absolute calibration of wide field imagers might be a solid routine procedure instead of an artistic enterprise.

Acknowledgements. This work is partially supported by the MIUR-COFIN/2002028935 grant under the project *Stellar Populations in Local Group Galaxies*

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