Astrometry of resolved stellar populations with MICADO at the ELT

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ABSTRACT

Precise astrometry will be one of the major benefits of a diffraction limited Extremely Large Telescope (ELT). The goal of the Multi-AO Imaging Camera for Deep Observations (MICADO), one of the first light instruments for the ELT, which is designed to work together with the Multi-Conjugate Adaptive Optics facility MAORY, is a relative astrometric precision of 20 μas, with the requirement being set at 50 μas. By achieving such a requirement, a wealth of currently open science cases will be investigated that will lead to an unprecedented understanding of the formation and evolution of the Local Group and its stellar populations. After describing MICADO primary science cases, in this paper we present the results on the first related scientific simulations. By using the most up-to-date instrumental Point Spread Function to simulate the central region of a Galactic globular cluster, we find that in case of perfect geometric distortion correction the precision achieved over a typical exposure of one minute already verifies the precision requirement of 50 μas. On the other hand, when introducing realistic distortions and using *Gaia* stars as reference to correct for them, we find that the final global astrometric precision exceeds the requirement by a factor of four, whereas local differential astrometry achieves 80 μas precision within a scale of 1 arcsec.

Keywords: Astrometry, Extremely Large Telescopes, Adaptive Optics, Globular Clusters

1. INTRODUCTION

Astrometry is one of the major drivers for a diffraction limited Extremely Large Telescope (ELTs). To reach diffraction limited observations, the Multi-AO Imaging Camera for Deep Observations (MICADO[1,2]), the first light infra-red camera for the ELT, will be assisted by an Adaptive Optics module (MAORY[3]) that will provide both a Single Conjugate (developed jointly with the MICADO consortium) and a Multi Conjugate modes. The ambitious goal of MICADO is a relative astrometric accuracy for bright and isolated stars of 20 μas, with the requirement set at 50 μas. To determine if such a performance is feasible, it is first necessary to assess how well MICADO geometric distortions can be calibrated.

MICADO calibration plan is to use pinhole mask(s)[4] to calibrate for high-order distortions, and to use on-sky observations to calibrate low-order distortions that will vary depending on the parameters of each observation (atmospheric conditions, geometry of the guide stars asterism, etc.). On-sky calibration usually exploit either

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standard calibrators, meaning sources (stars or quasars) for which the position is known very precisely (with a precision comparable to the requirement,[5] or observations of dense stellar fields purposedly dithered to enable the application of self-calibration techniques.[6,7]

In this paper we focus on the first of these methods. By using realistic simulations of MICADO observations of a Galactic globular cluster, and by exploiting *Gaia*[8] stars as standard calibrators (and assuming *Gaia* end-of-mission performance) we test how well MICADO geometric distortions[9] can be calibrated. Based on the achieved astrometric precision after the correction of distortions, we then draw conclusions on the strategy to follow in order to be able to succesfully investigate MICADO primary astrometric science cases.

The paper is structured as follows. The primary science cases are described in Sect.2. Sect.3 is dedicated to the description of the setup for the simulations and the geometric distortion correction. The results of our test are presented in Sect.4, and the conclusions are finally drawn in Sect.5.

2. MICADO PRIMARY ASTROMETRIC SCIENCE CASES

1. *The Galactic centre.* The Centre of the Milky Way is a unique laboratory for exploring strong gravity around the closest massive black hole we know of at a level of detail and quality that will never be possible in external galaxies. MICADO is uniquely suited for the exploration of the Galactic Centre, as the stellar cusp is strongly confusion limited for current AO observations on 8m class telescopes. This limits the reliable detection and measurement of the positions of stars to K$\simeq$16-17.5.[10] The combination of MICADO and the ELT will increase the sensitivity by > 5 magnitudes in modest integration times, making astrometric studies of even sub-solar mass stars with a long term precision of 50 μas possible. This level of precision will enable the determination of the orbits of very faint (K$< 20-21$) main sequence stars in the inner cusp, with semi-major axes significantly smaller than the current S-stars. Such stars would have orbital time scales of a few years, and so the Schwarzschild precession and other general relativity terms will be detectable in a decade of observations.

2. *Intermediate mass black holes (IMBH) in globular clusters.* Super-massive black holes seem to exist in the centre of most massive galaxies, but the mechanisms that lead to their growth from a first black hole seed are still matter of debate. In this sense, the mass of the seed is a fundamental parameter, because based on its value different scenarios are likely. By extrapolating the observed relation between the mass of the black hole and that of the host system,[11] the most promising candidates to host IMBH ($\sim 10^4 - 10^5 M_\odot$) are globular clusters. The hunt for IMBH in these systems started years ago, but has resulted in no robust detection so far.[12,13] Arguably, one of the best ways to look for IMBH is kinematically, as IMBH build a cusp in the velocity dispersion profile of the innermost region (~ 1 arcsec) of a globular cluster. However, so far these extreme regions have remained inaccessible to the current instrumentation, as the best proper motions available nowadays thanks to *Hubble Space Telescope* observations[14] can only resolve the inner few arcseconds. Thanks to its outstanding resolving power and sensitivity, MICADO will be able to access this central cores and to tell once for all whether IMBH inhabit the center of globular clusters or not.

3. *Dark matter in dwarf spheroidal galaxies.* One of the current open problems of Λ-cold dark matter cosmology concerns the shape of dark matter halos on the scales of the smallest galaxies, i.e. the so-called cusp-core problem.[15] It appears that the observed internal density profile of dwarf galaxies is less steep than predicted by cold dark matter simulations. One of the best way to solve this problem is to measure the internal kinematics of stellar systems living in pristine dark matter halos, like the dwarf spheroidal galaxies satellites of the Milky Way. Thanks to the combination of *Gaia* and *Hubble Space Telescope* data separated by > 10 years it has recently been possible for the first time to determine the internal proper motions in the Sculptor[16] and Draco[17] dwarf spheroidals. However this was only possible in regions that were too far away from the galaxies centres to be sensitive to differences between cuspy or cored dark matter profiles, which is how the cusp-core problem can be solved.[18,19] Thanks to the astrometric capabilities of MICADO, measurements of proper motions in the cores of dwarf spheroidals can be achieved with a relatively short time baseline of only 5 years.

The success in investigating these science cases will rely on the long-term stability of the MICADO astrometric performance, this in turn depends on our ability to correct the geometric distortions. In the following we will test what is the expected astrometric precision achievable when correcting geometric distortions on-sky, using *Gaia* stars as reference.

3. MICADO GEOMETRIC DISTORTION CORRECTION

To carry out our investigation, we simulate the crowded stellar field of a Galactic globular cluster. Globular clusters are ideal astrophysical objects to calibrate geometric distortions on sky because of the availability of many bright stars that populate homogeneously the field of view. In our case, we are especially interested in those brighter than *Gaia* magnitude limit, that is G$\simeq$21. These stars will in fact have precise measurements of their position and proper motion, and they can effectively be used as standard astrometric calibrators at the time of MICADO observations.

In our investigation we simulate only the central chip of MICADO (size of about 16×16 arcsec^2), where we assume the MAORY diffraction limited PSF[20] to be constant across the entire field of view. This is obviously a strong assumption. However several previous studies have demonstrated that the PSF in AO images varies in a way that is very difficult to predict.[21–24] Therefore, we postpone the investigation of the case of a variable PSF to future works.

The simulated globular cluster follows the density profile observed for the cluster M3[25] and the luminosity function predicted by the theoretical models taken from the Basti archive ([26]). The software used to create the simulated images is described in detail in Deep et al. 2011,[27] while the updated technical specifications used for these simulations are described in Massari et al. 2016.[28]

The simulations are performed in the MICADO standard resolution mode (4 mas/pixel), in K-band (with a Strehl ratio of 37%), with an exposure time of 60 s and assuming stars brighter than K=15.5 to be saturated.[2] Geometric distortions including the contribution coming from MICADO and the ELT are taken from Rodeghiero et al. 2018[9] (using a polynomial description up to the 5th order) and are applied directly to the input catalog positions. An example of such simulations is shown in Fig.1.

4. RESULTS AND DISCUSSION

At this point we perform two tests. One is to determine MICADO astrometric precision in case of perfect geometric distortion correction. The other is to deterime how precisely we can correct MICADO distortions using real *Gaia* stars as calibrators.

4.1 Perfect geometric distortion correction

To simulate the case of a perfect geometric distortion correction, we compared the stellar positions as measured in two dithered images independently simulated with no geometric distortions. The resulting astrometric precision is defined as the dispersion around the mean value of the distribution of (X_{input}-X_{output}) and (Y_{input}-Y_{output}), and its trend against the input K-band magnitude is shown in Fig.2.

We found an astrometric precision for the brightest unsaturated stars of $\sigma_X = 13\ \mu as$ and $\sigma_Y = 20\ \mu as$, which correspond to the expectations for star with a signal-to-noise SNR$\simeq$ 300 using the Lindegren formula.[29] This outstanding performance obtained accross the whole field of view would naturally ensure the feasibility of all of the primary science cases.

4.2 Realistic geometric distortion correction

To simulate a realistic case of distortions calibration using *Gaia* stars we followed the following procedure.

1. First, we distorted the input positions using a 5th order polynomial describing the geometric distortions investigated by Rodeghiero et al. 2018.[9] These take into account the distortion terms coming from MICADO and the ELT, thus neglecting all of those related to MAORY. We refer the reader to the quoted paper for more details.

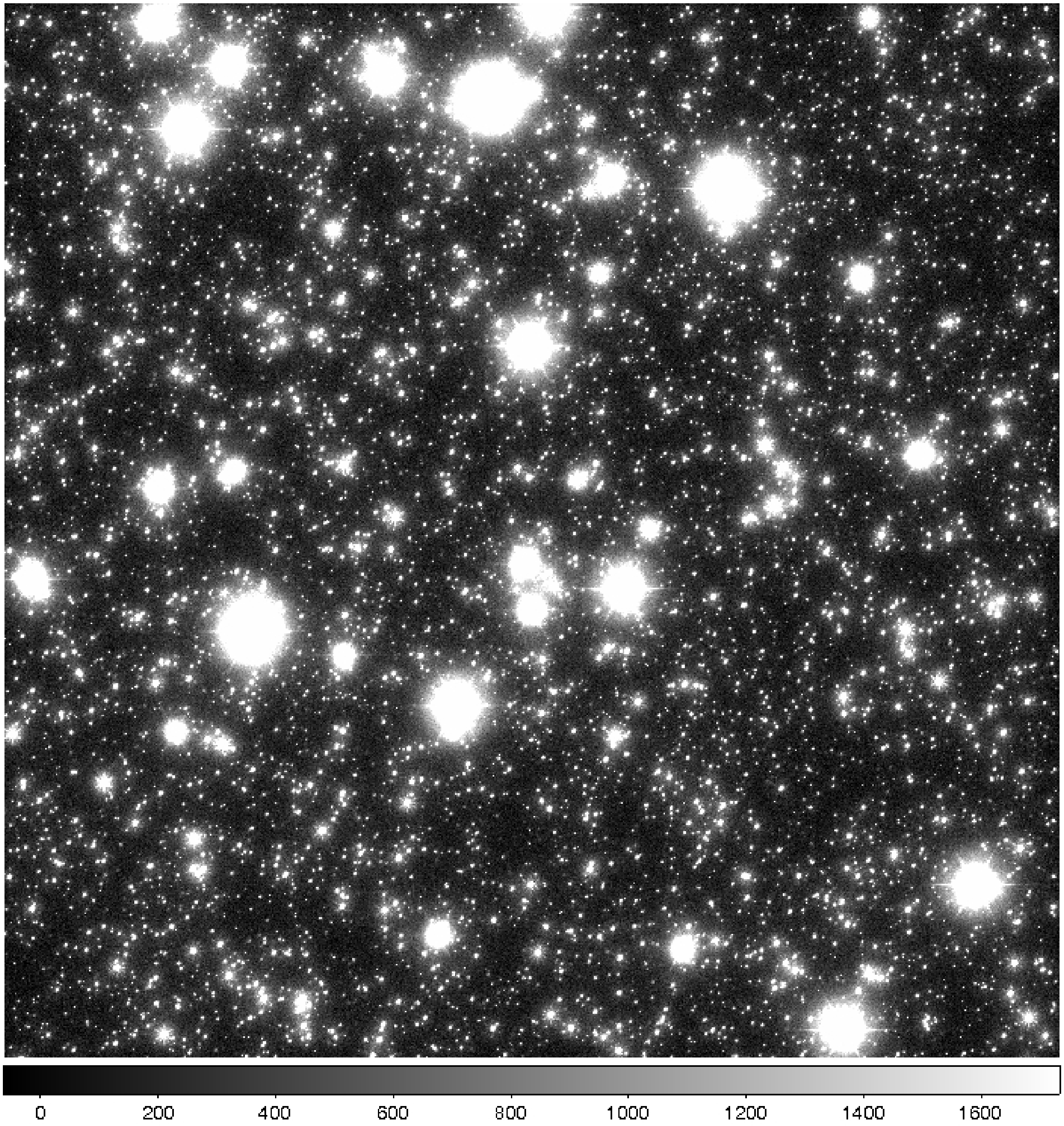

Figure 1. Example of one of the simulated stellar fields analysed in this work. The image is a 60 s simulated exposure of the inner 16×16 arcsec^2 of the globular cluster M3 taken in the Ks band with MICADO.

2. Once the images have been simulated, we defined all stars with input G-band magnitude G$<$ 21 as *Gaia* stars.

3. To determine the positional uncertainty on *Gaia* stars at the time of MICADO observations (assumed to be in 2025), we took the *Gaia* end of mission prescriptions as function of magnitude

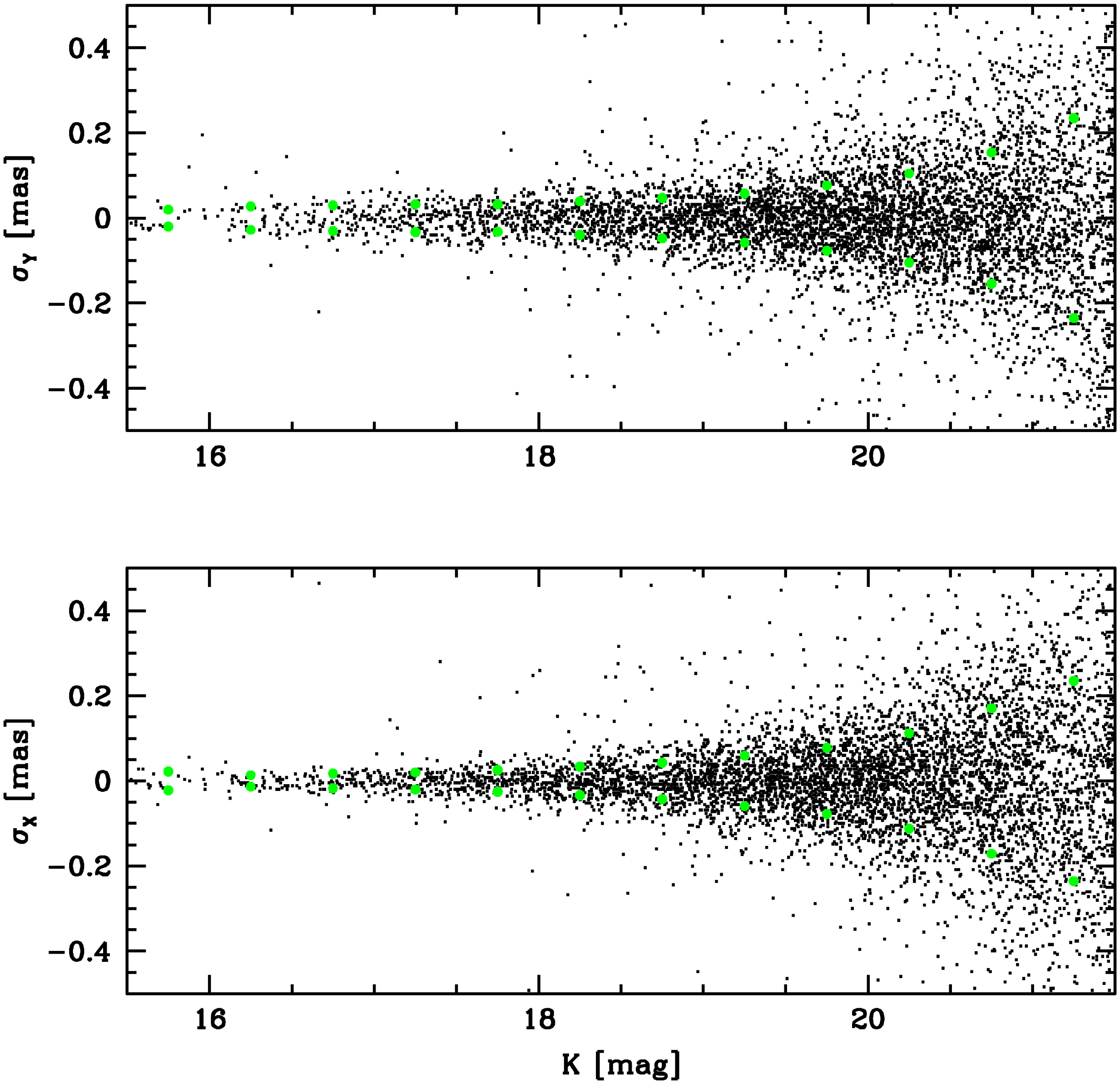

Figure 2. Global astrometric precision as function of K-band magnitude in case of perfect distortion correction. Green filled circles indicate the value of the precision for different magnitude bins.

(`https://www.cosmos.esa.int/web/gaia/science-performance`) and colour and computed the uncertainty σ_{2025} as:

$$\sigma_{2025} = \sqrt{\sigma_{eom}^2 + [(2025 - eom) * \sigma_{PM}]^2}, \tag{1}$$

where σ_{eom} is the positional precision predicted at the *Gaia* end-of-mission, σ_{PM} is the prediction for the proper motion end-of-mission uncertainty and *eom* is the epoch at which *Gaia* ended its nominal mission, that is 2019.5. The X and Y componets (assumed to be aligned with Right Ascension and Declination), were treated separately, following with their own individual *Gaia* prescription.

4. At this point, we simulated such a positional uncertainty by replacing the input positions of *Gaia* stars with a *perturbed* position obtained by randomly extracting a value from a 2-dimensional Gaussian distribution centered around the input position and with dispersions in the X and Y directions corresponding to the uncertainty on the two positional componets in 2025 ($\sigma_{X,2025}, \sigma_{Y,2025}$).
5. We then used the 56 *Gaia* stars with $\sigma_{2025} < 500$ mas for which we obtained a (distorted) positional measurement to compute a 3rd order polynomial (no higher order was achievable given the number of calibrators) distortion model.
6. Finally, we applied such a distortion model to all of the measured stars to obtain distortion-corrected positions.

The results of the distortion correction when applied globally on the entire field of view are shown in Fig.3. We found an astrometric precision for bright unsaturated stars of $\sigma_X = 160\ \mu as$ and $\sigma_Y = 190\ \mu as$.[*] *This precision is totally driven by the uncertainty on the Gaia stars proper motions in 2025.* In fact, the typical positional error for the sample of *Gaia* stars is $\sigma_{2025} = 350\ \mu as$, to which the uncertainty on the proper motions propagated by the (2025-*eom*) temporal baseline contributes for more than the 90%. Starting from this typical error, the expected precision on the geometric distortion solution (which being in the shape of a third-order polynomial has $\mathrm{N}_{f-p} = 10$ free parameters) scales as:

$$\sigma_{exp} = \sigma_{2025}/\sqrt{N_{Gaia\ stars}/N_{f-p}} = 350/\sqrt{56/10} \simeq 150\ \mu as, \tag{2}$$

which matches remarkably well our findings.

These values exceed the nominal requirement. However, it should be underlined that these numbers apply to the *global* correction. In other words, this is a measure of the precision for *absolute* astrometry. MICADO requirement is set on relative, differential astrometry. A better estimate for this parameter is therefore provided by the precision on the distances between pairs of stars as a function of the spatial scale. Closeby stars should suffer less from the geometric distortions, that are locally less intense.[9] This is in fact confirmed by the results summarised in Fig.4.

The precision on the distance between pairs of stars worsens with increasing distance, and for stars closer than 250 pixels (corresponding to 1 arcsec), the precision reaches a level of 80 μas, much closer to the MICADO requirement.

5. CONCLUSIONS

In this paper we have assessed how precisely MICADO geometric distortions can be corrected when using *Gaia* stars as reference. In case of perfect correction, the astrometric precision achieved by MICADO will be of 10-20 μas, thus ensuring the feasibility of the primary astrometric science cases. In case of realistic correction, our findings demontrate that the uncertainty on the proper motions of *Gaia* stars dominates the precision achievable on the distortion correction. When considering a global correction across the entire field of view, the best precision achieved on the brightest stars is $\sim 160\ \mu$as. When instead focussing on relative, differential astrometry on local scales, the achieved precision reaches 80 μas within a spatial scale of 1 arcsec. These numbers demonstrate that the extension of the *Gaia* mission will also be beneficial for MICADO, as the predicted improvement on the proper motions by more than 40% should be enough to achieve MICADO astrometric requirement. Alternatively, for specific targets the combination of *Gaia* with existing *Hubble Space Telescope* observations providing longer temporal baselines[16, 17, 30] could be a viable solution, too.

The realistic case investigated here refers to the observations of a Galactic globular cluster, a dense environment where the number of available *Gaia* calibrators will be sufficiently large to ensure good calibration. Future efforts will be devoted to test whether a sufficient correction can be achieved in less dense environments (like dwarf spheroidal galaxies), as well as when considering more complex simulations, for example including spatial variations of the PSF.

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[*] The rise of the trend for the Y-component at the brightest magnitudes is likely due to small number statistics.

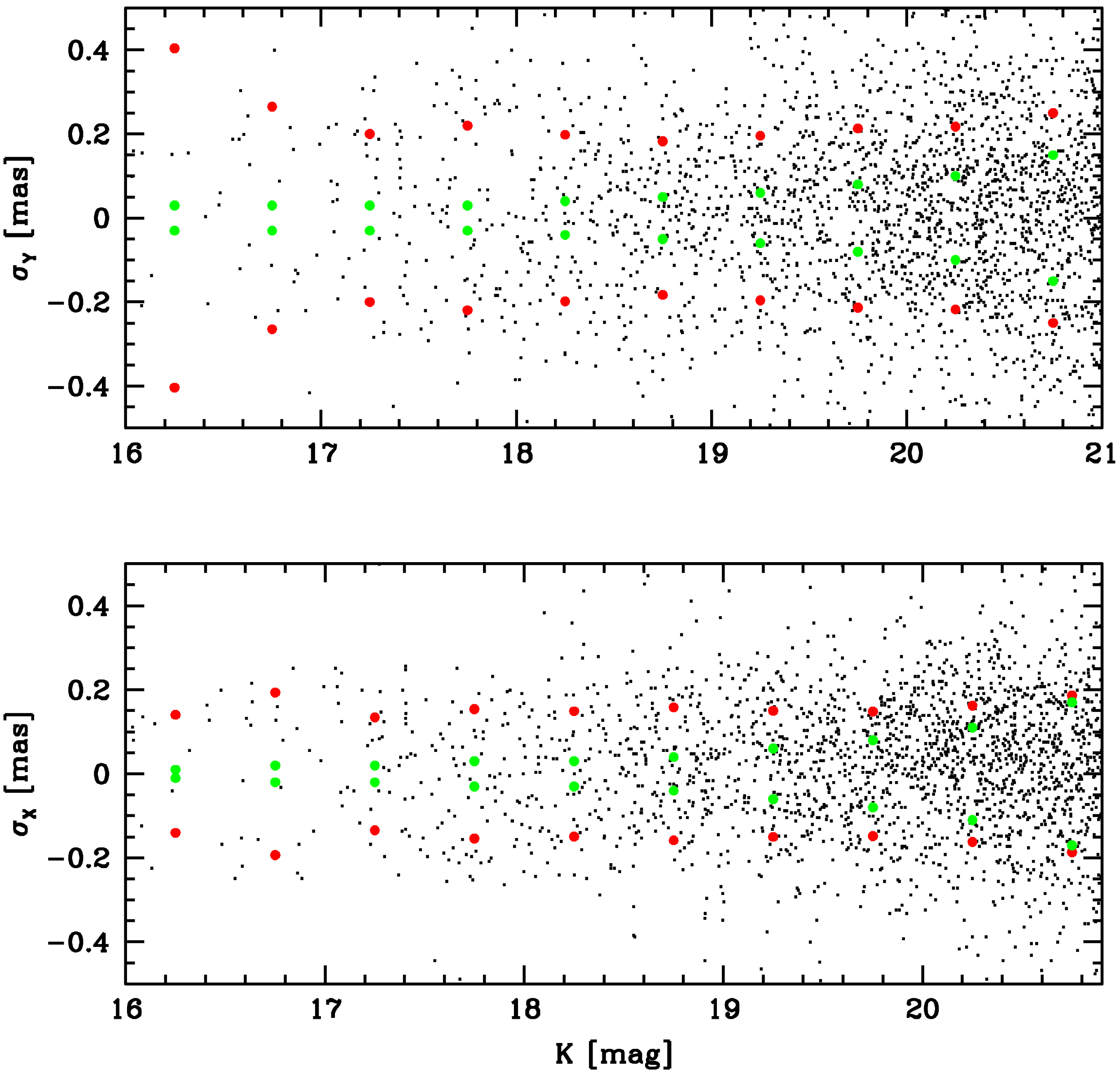

Figure 3. Same as in Fig.2 but in case of realistic correction. Red circles show the achieved precision for different magnitude bins, whereas green circles correspond to the idealised case and are shown for sake of comparison.

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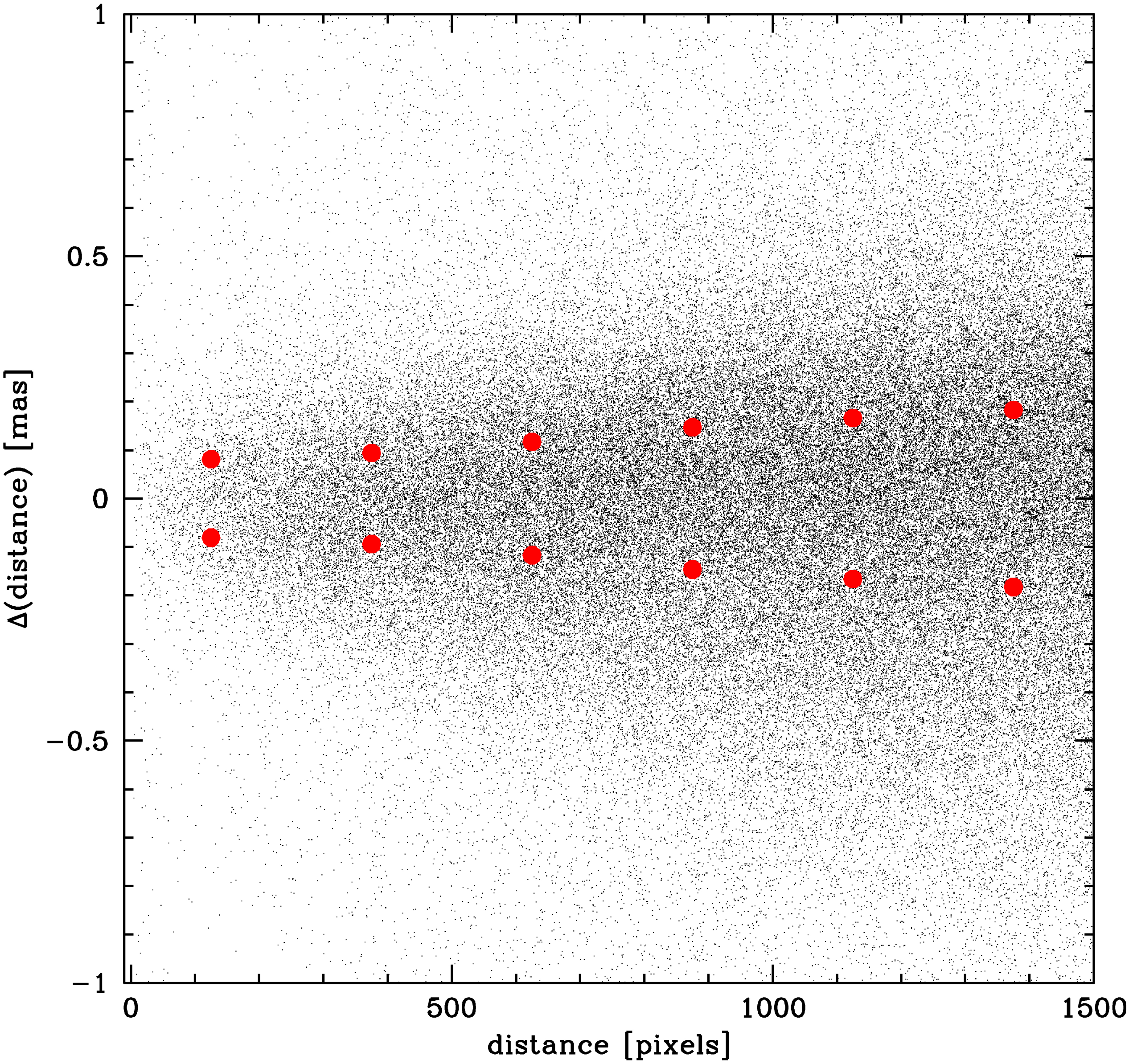

Figure 4. Precision on the distance between two stars as a function of their separation. The red dots correspond to the precision achieved in distance bins of 250 pixels (the pixel scale is 4 mas/pixel).

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