Enabling precision astrometry science in TMT era

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Problem

In a few words, what is this all about? The astrometric precision of ground based telescopes is decreased by the effect of atmospheric turbulence. We are developing methods for compensating for this error.

How is this issue typically dealt with? Without adaptive optics, the best we can do from the ground is to increase exposure time and the number of exposures. Using adaptive optic systems, it is possible to compensate for most of the atmospheric turbulence, but it is necessary to consider the effect of the AO system itself on the astrometric precision.

What is the significance of this study? The next generation of big telescopes will use Multi Conjugate Adaptive Optic (MCAO) technology which provides widefield (~1') diffraction limited resolving power (i.e. NFIRAOS for TMT). This opens the door to many new astrometric studies, from measuring the stars orbiting SMBH in the center of the Milky Way to studying the internal kinematics of globular clusters. This is only possible if we can develop methods to use these new instruments up to their expected capabilities. The significance of this study is to consider the effect of the AO system (specifically MCAO systems) on the astrometric performance, characterize it, and possibly develop methods to deal with it.

Approach

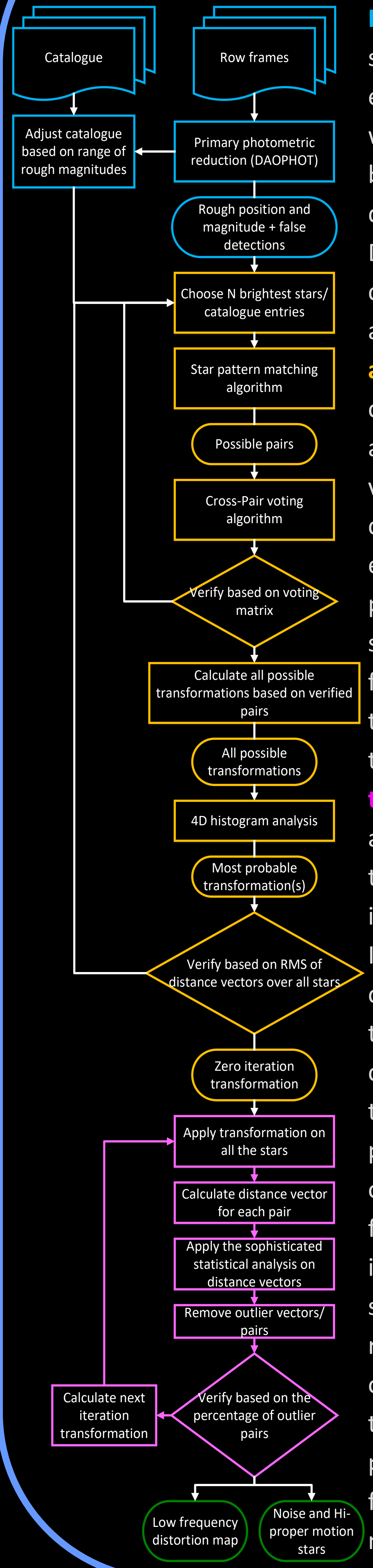
We are using the only existing MCAO system (GeMS/GSAOI) and globular cluster core observations (NGC6723) to better understand the astrometric performance of such systems, as well as developing a method to measure and deal with different sources of distortions. Ultimately, the outcome of this research seeks to obtain the best possible astrometric precision from the next generation of ground-based telescopes.

Why a globular cluster? Dense field observations are easier for relative astrometric characterisation and for measuring the performance of our method.

What are the steps of this approach? After performing typical photometric reduction, we use a voting based star pattern matching algorithm to match a few stars between two fields or a field and a target catalogue. In the second stage, a 4D histogram analysis provides a set of matched transformations between the two sets. In the final step, an iterative verifier checks and corrects the transformation using all the stars in the field. Simultaneously, sophisticated statistical analysis, low-spatial frequency distortion, false star detection, and high proper motion stars would be recognised and separated from each other.

What are the potential benefits? This approach is simpler and faster than typical astrometric reduction methods, which deals with each error factor separately. Also, it measures low spatial frequency distortions (e.g. instrument distortion map) utilizing fewer observations. Ultimately, we are working on a method originating from this approach to measure the AO system astrometric performance.

Method



Catalogue

Row frames

Adjust catalogue based on range of rough magnitudes

Primary photometric reduction (DAOPHOT)

Rough position and magnitude + false detections

Choose N brightest stars/ catalogue entries

Star pattern matching algorithm

Possible pairs

Cross-Pair voting algorithm

Verify based on voting matrix

Calculate all possible transformations based on verified pairs

All possible transformations

4D histogram analysis

Most probable transformation(s)

Verify based on RMS of distance vectors over all stars

Zero iteration transformation

Apply transformation on all the stars

Calculate distance vector for each pair

Apply the sophisticated statistical analysis on distance vectors

Remove outlier vectors/ pairs

Verify based on the percentage of outlier pairs

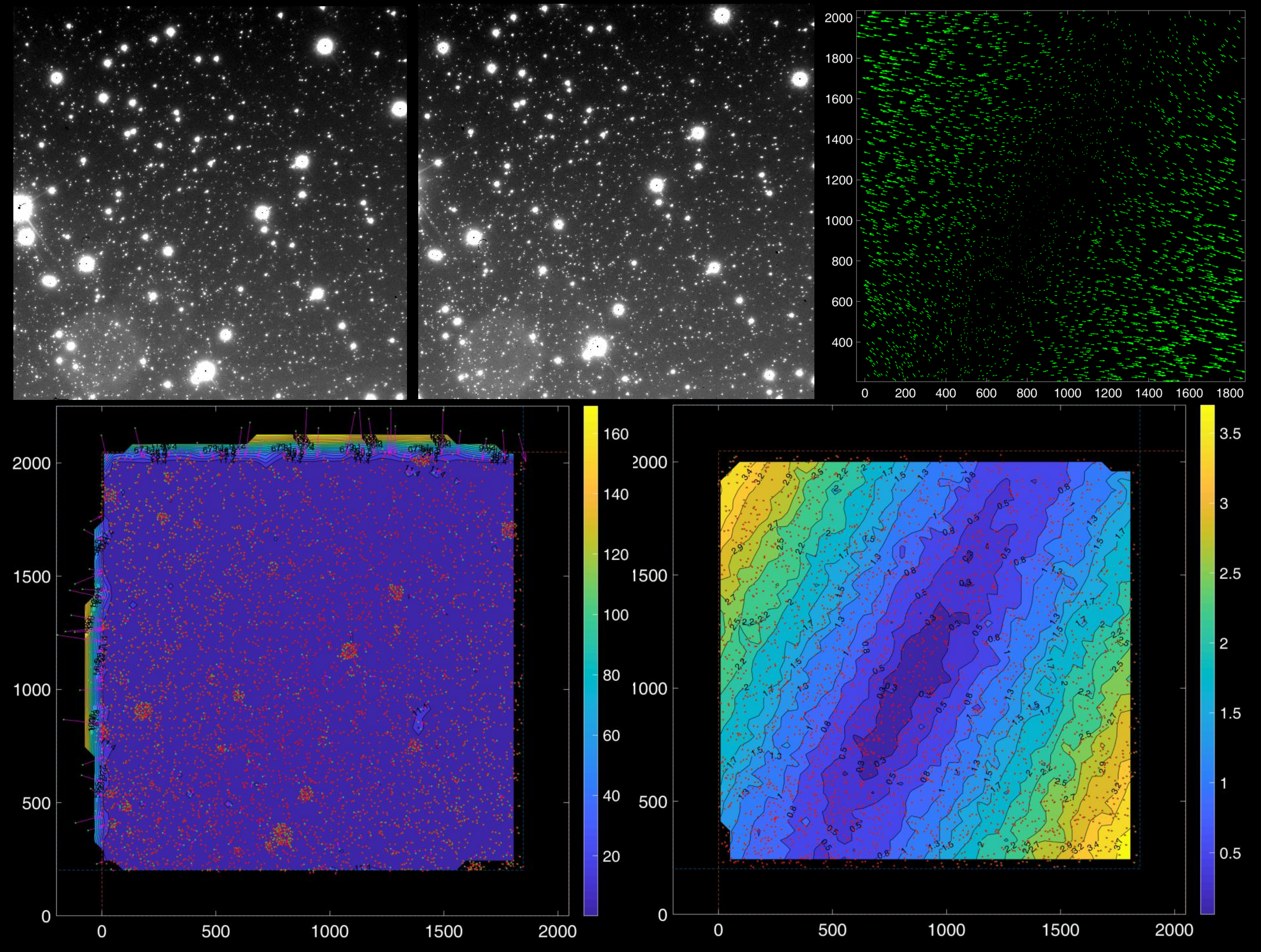
Calculate next iteration transformation

Low frequency distortion map

Noise and Hi-proper motion stars

Input and data preparation: This algorithm needs two sets of inputs. Each input could be an exposure, set of exposures or an astrometric catalogue. The aim of the whole process is to find the best transformation between these two sets of inputs and categorize different types of astrometric errors between the two. Data preparation procedure for exposures mainly consists of typical photometric reduction (DAOPHOT) and for catalogues is magnitude thresholding. **Finding and verifying iteration zero transformation:** This stage could be divided into two sub sections: the voting algorithm and 4D histogram analysis. In summary, the voting algorithm finds best possible candidate pairs for creating transformation using a few selected stars from each input sets. The 4D histogram step would create all possible transformations out of these pairs based on simultaneous histogram analysis of each degree of freedom, suggesting the best transformation. This is the first transformation which we call iteration zero transformation. **Sophisticated statistical analysis and the iterative process:** This step is the heart of this algorithm. In the beginning, the iteration zero transformation is applied to all stars of one set of inputs and the result is projected on the other set. Ideally, all the transformed stars should fall on their counterpart, but because of different distortion errors, they fall in the vicinity of their counterpart. After calculating all the vectors connecting each pair of stars, the statistical iterative process would remove high proper motion stars (in the case of long epoch observations) and noise (false star detections) from the field. In summary, this process compares each vector to its neighbour vectors. If the behaviour of the vector is statistically different relative to its neighbours, it will be removed. The process would end when the percentage of removed pairs in each iteration falls below a certain threshold. **Output:** The output contains two sets of pairs: one set are the pairs which build the low spatial frequency distortion map. The other set consists of noise and high proper motion stars.

Results



Top left and middle: Reduced exposures of NGC6723 core. Note the relative shift caused by telescope dithering. **Bottom:** The output of this algorithm on the exposures above. The two frames are transformed and matched on top of each other. The blue and orange dash lines show the border of each frame. Each red dot indicates one pair of stars. The **left** image is the result just before the iterative process and the **right** one is after 6 iterations, which reduces number of pairs from 4803 to 3108. Removed stars are combination of noise (false detection e.g. the region around bright stars) and high-proper motion stars (long epoch observations). The unit of the colour bar is detector pixels (1p=0.02") and the plot is color coded by the intensity of distortion. **Top right:** Vector field of the distortion map on the bottom right. The RMS of the intensity of the distortion field for this data is 0.0325".

Future work

What are the next steps?

- First publication is under review, mainly containing the methodology, distortion modeling and proper motion measurements of NGC6723 core.
- More in-depth science and CMD analysis in ongoing for the second publication.
- Working towards GeMS-GeMS astrometry by analysing new observations (ID: GS-2019A-Q-203, PI: M.Taheri)