Jean Ballet, CEA/DAp 27 April 2022

EPIC MOS astrometry

Long known that astrometry is not as good off-axis

- ✓ Christian Motch's breakthrough
- ✓ Source detection separately for each instrument
- ✓ Aligning MOS to PN
- ✓ Results
- ✓ PN absolute astrometry

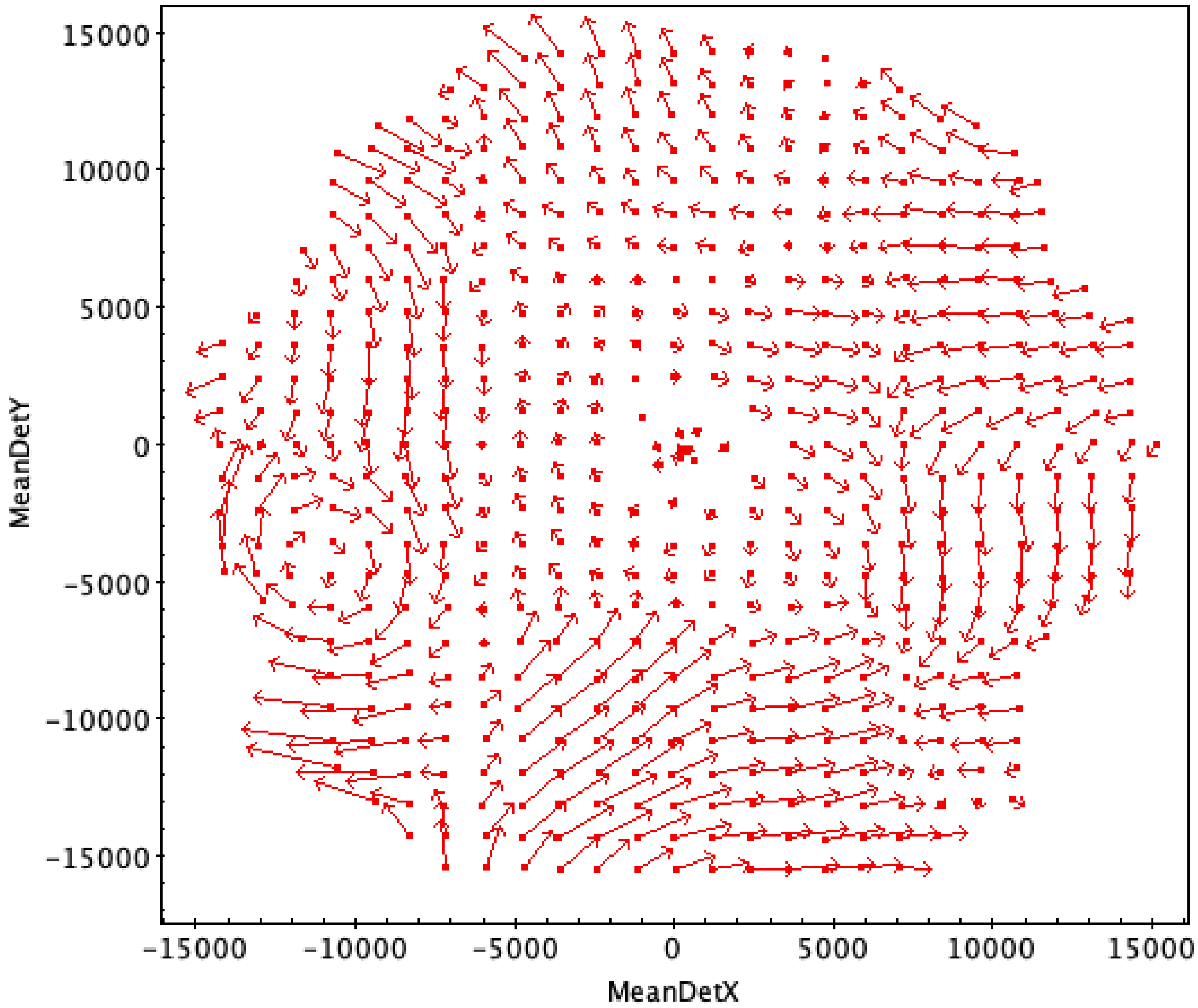
The problem

C. Motch (Obs. Strasbourg) at the SSC consortium meeting in October

Average **offsets** between XMM positions and counterparts (amplified)

Follow the structure of the **MOS CCDs**

Implies that **the outer MOS CCDs are not at the right place** in the CCF



The algorithm

1. Extract source positions separately for each camera (PN, MOS1, MOS2)
2. Correlate sources between the cameras. Does not require any catalogue associations (purely internal, any good point source will serve)
3. Compute offsets between MOS1/2 and PN (used as reference)
4. Deduce X/Y shifts and rotation for each MOS CCD

Iris Traulsen (AIP) has images of all stacked observations in stacked coordinates (does not matter as long as we can get back to detector coordinates)

She selected **1314 suitable observations** (OBS_CLASS <= 2, PN in full-window mode and not too big stacked images) and processed them before Christmas, providing **one source list per observation and camera** (from a common eboxdetect input list)

She added detector coordinates to each source list, achieving item 1.

Source selection

1. Start from the 4XMM-DR11 catalogue, which contains flags allowing to select good sources (not available in the per-camera source lists)

2. Select all sources in one of the observations processed by Iris, with EP_EXTENT=0, DIST_NN (distance to nearest neighbour) > 20”

3. Associate by RA/Dec with each source list per camera, with loose tolerance max(RADEC_ERR, 2”) x 2.15 (➔ 99% error circle)

4. Keep only sources with EXT=0, DET_ML>6 in full band, MASKFRAC>0.7, PILEUP<1 and no flag in current instrument

5. Copy detector coords and error from current camera to global source list

Result is consolidated list of **45,202 good PN sources** with only one row per source and detector coordinates from each camera.

33,733 M1 detections (2 CCDs missing now) and **41,207 M2** detections

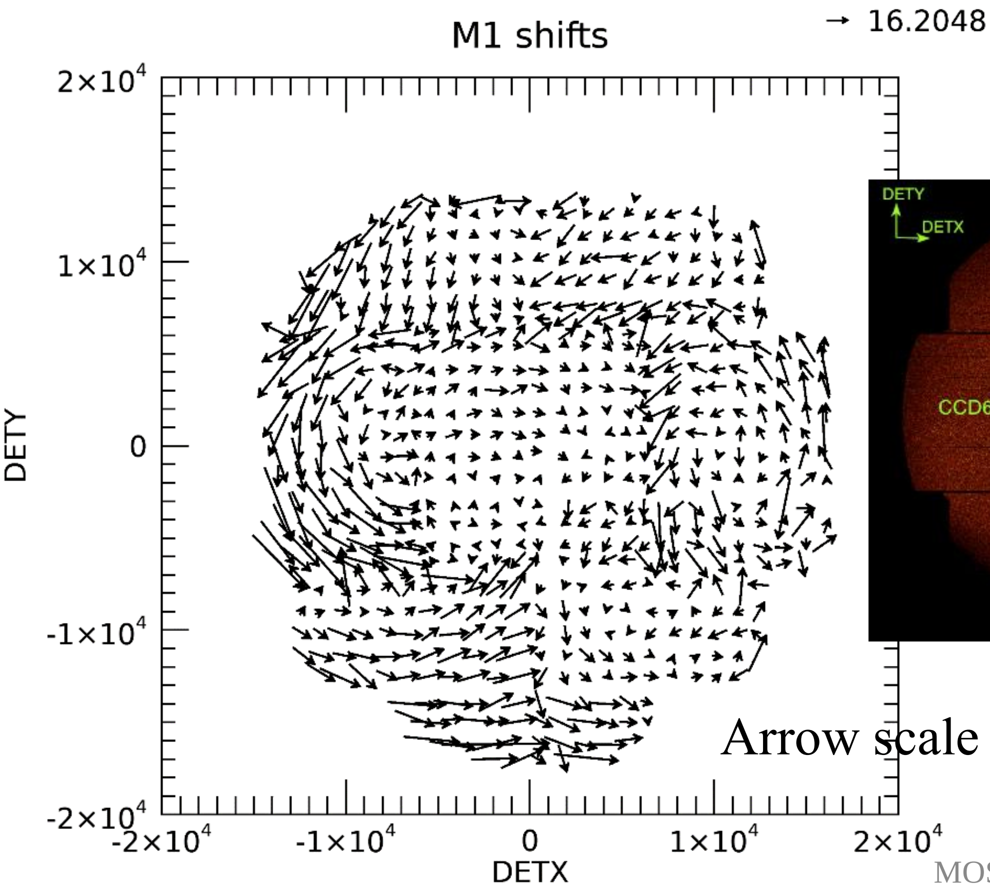
Convert detector coordinates

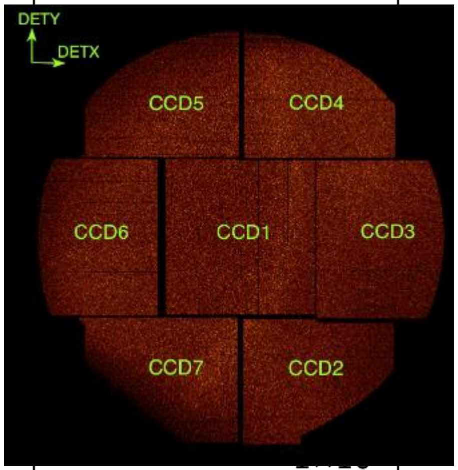
1. The detector coordinates are specific to each camera; they are not aligned
2. But they have exactly the same scale of 0.05”, so the transformation is a simple rotation-translation
3. I extracted from a particular observation detector coordinates in each camera of 4 points at the same X/Y close to the corners of the FOV
4. I extracted the rotation-translation from that (4 points are redundant so I could check it works well)
5. The rotation from PN to M1 is close to +90°, that from PN to M2 to 180°

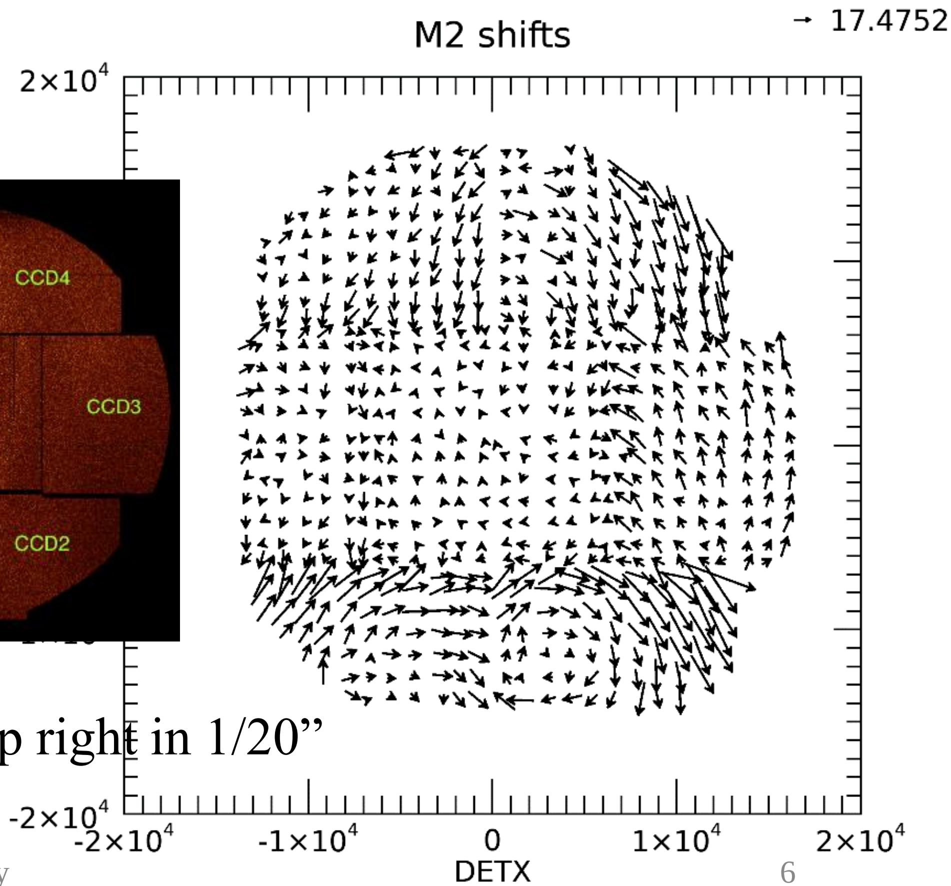
Result: PN source coords converted to M1 or M2 detector coords

Detector coordinate shifts

1. Error Δ quadratic sum of PN and MOS error + **1” systematic**
2. **Weight as 1/Δ** (compromise between many sources and good localization)
3. Average shifts over sources in 1x1 arcmin bins, not mixing CCDs







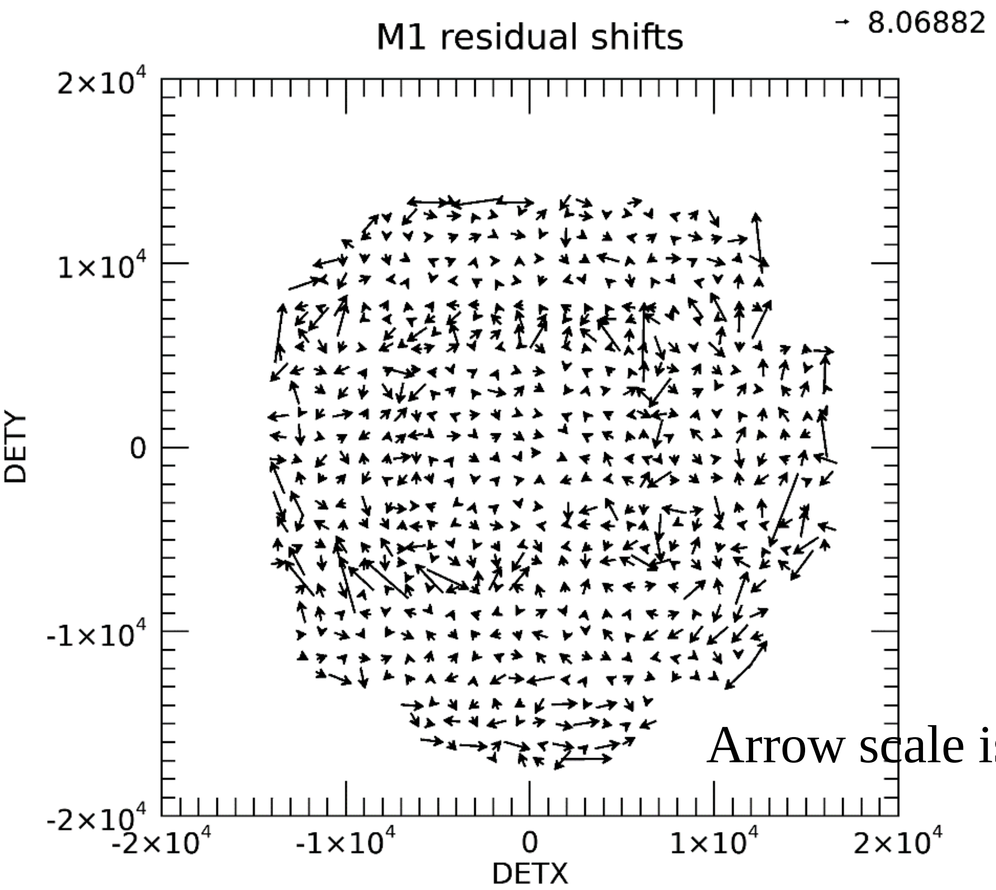
Arrow scale is at top right in 1/20”

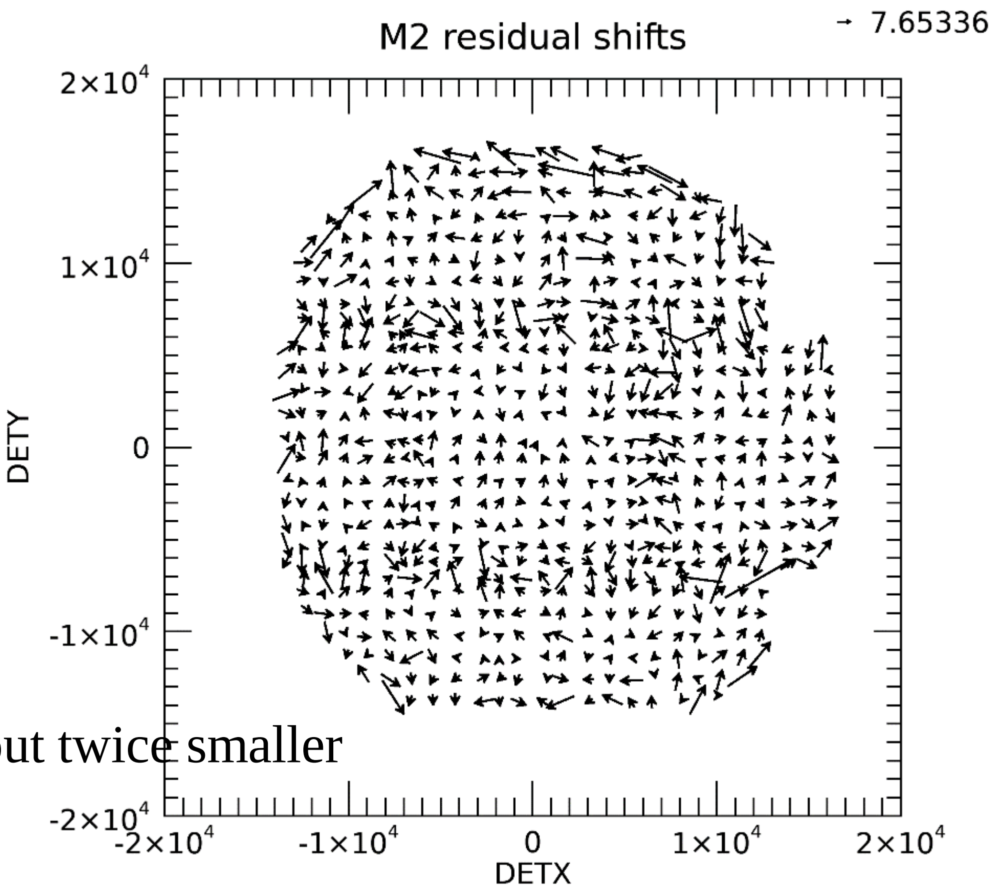
Extract geometric transformation

1. Select sources in one CCD only
2. 4 dof per CCD: scale factor a, angle θ, shift $\vec{S} = \binom{SX}{SY}$
3. Remove barycentre $\vec{B}$ from MOS and PN coords: $\vec{D} - \vec{B} = \overrightarrow{DD} = \binom{DX}{DY}$
4. $a = \sum \frac{\overrightarrow{DD_{\mathrm{PN}}} \cdot \left(\overrightarrow{DD_{\mathrm{PN}}} - \overrightarrow{DD_{\mathrm{MOS}}}\right)}{\Delta} / \sum \frac{\mathrm{DD}_{\mathrm{PN}}^2}{\Delta}$
5. $\sin\vartheta = \sum \frac{(DX_{\mathrm{MOS}}\, DY_{\mathrm{PN}} - DY_{\mathrm{MOS}}\, DX_{\mathrm{PN}})}{\Delta} / \sum \frac{\mathrm{DD}_{\mathrm{PN}}^2}{\Delta}$
6. Apply rotation and scaling $\overrightarrow{DR} = (1 + a)\, ROT(\vec{D})$
7. Deduce shift (at FOV center) $\vec{S} = \sum \frac{\overrightarrow{D_{\mathrm{PN}}} - \overrightarrow{DR_{\mathrm{MOS}}}}{\Delta} / \sum \frac{1}{\Delta}$

Apply geometric correction

1. Apply transformation to each MOS source
2. New = (1+Scale) x ROT(Old) + Shift

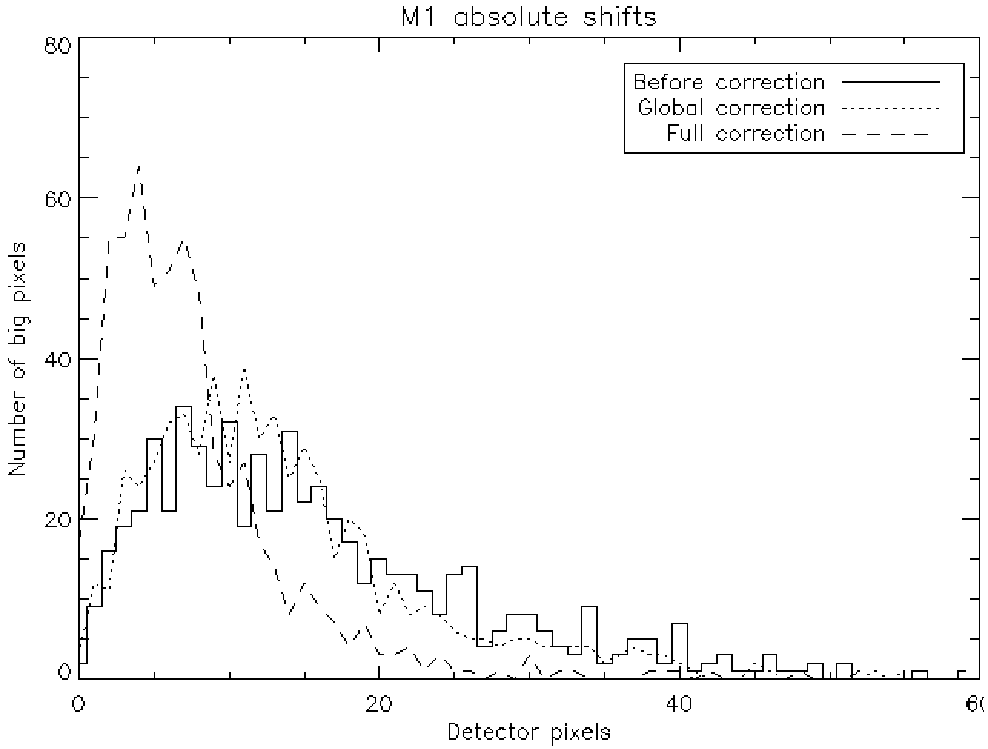


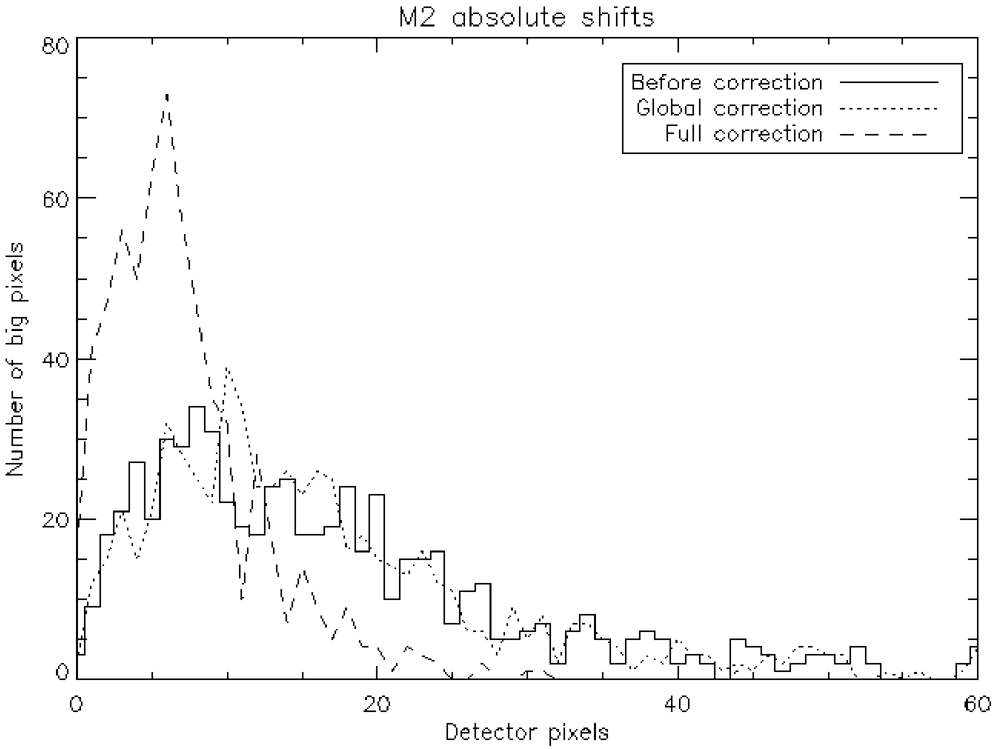


Arrow scale is about twice smaller

Improvement after correction

1. No improvement at focal plane level, only **at CCD level**
2. **Median absolute shift** M1: 14.0 ➔ 6.6M2: 14.6 ➔ 6.6 det pixels
3. **M1 χ^2** 3724/609 ➔ 861/581 **M2 χ^2** 7154/638 ➔ 1085/610





Results

Inst	CCD	NSRC	SX	SY	ΔS	θ	$\Delta\theta$	a	Δa
			Det pixels (20 = 1”)			arcmins		1E-4	
M1	1	10895	+3.0	-0.4	0.4	-3.4	0.2	-0.1	0.5
	2	3491	+3.6	-2.8	0.8	+6.6	0.5	-3.8	1.4
	3	3603	-3.4	-1.1	0.8	+9.3	0.4	+14.5	1.2
	4	3800	-10.6	-6.6	0.7	-1.1	0.5	+5.9	1.4
	5	4007	-2.8	-11.7	0.7	+5.1	0.5	+17.2	1.4
	6	2117	+3.8	-16.1	1.0	+17.0	0.6	+13.0	1.7
	7	4263	+18.4	+3.4	0.7	+6.3	0.4	+10.7	1.2
M2	1	11519	-3.1	+0.5	0.4	-1.9	0.2	-2.0	0.5
	2	4509	+13.7	-14.7	0.7	-21.0	0.4	+10.8	1.1
	3	5160	-7.2	+13.4	0.6	+1.6	0.3	+8.4	1.0
	4	3973	+9.3	-19.0	0.7	-8.5	0.4	+6.6	1.2
	5	4787	-4.0	-13.5	0.6	-2.7	0.4	+3.3	1.1
	6	5278	+1.9	-4.9	0.6	-3.6	0.3	+4.3	1.0
	7	4083	+18.8	+7.1	0.7	-12.0	0.4	+14.2	1.2

Actual shift: 0.1 mm ➔ 2.8” ➔ 56 pix

Rotation of 10’ at CCD border ➔ 0.9”

Scaling of 10^{-3} at CCD border ➔ 0.3”

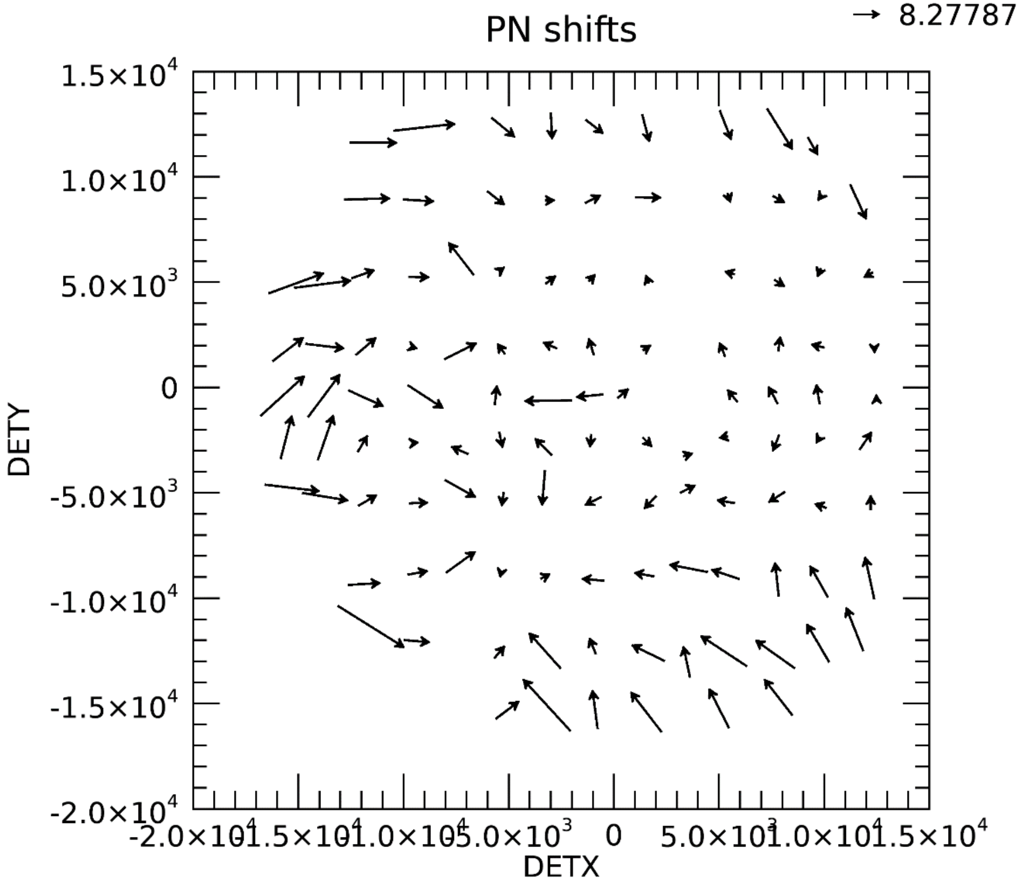
Shift is that of barycentre (not at FOV centre)

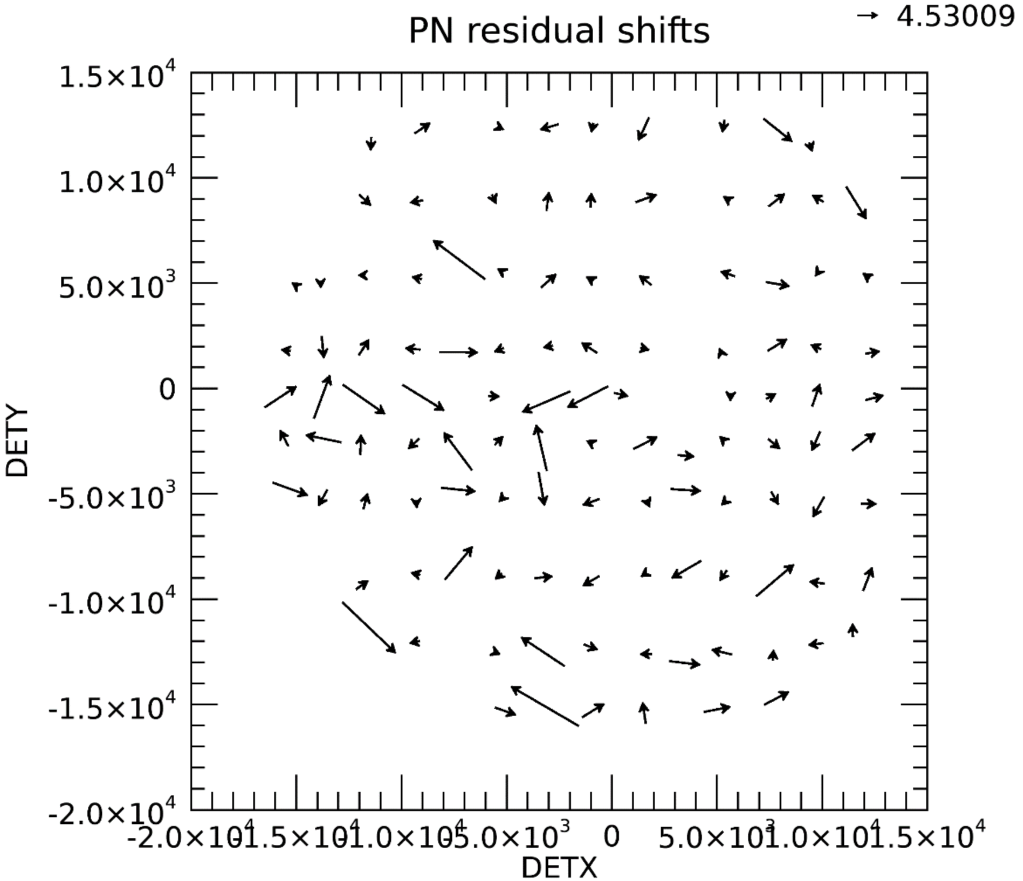
PN absolute astrometry (C. Motch)

1. Start from list of **46,963** PN-only detections
2. Cross-Match with best_milliquas.fits (best localised Million quasar positions)
3. End up with **6,046** matches (NB: 72,587 matches in full DR10)
4. Also tested GAIA EDR3 catalogue, but many more spurious matches
5. Provides counterpart positions in PN detector coordinates from which I can compute a correction

PN detector coordinate shifts

1. **Same method as MOS** (scale factor, rotation, shift at FOV centre)
2. Eliminate 39 outliers (more than 5σ shifts after correction)
3. Average shifts over sources in 3x3 arcmin bins, not mixing CCDs
4. Arrow scale is about twice smaller after correction





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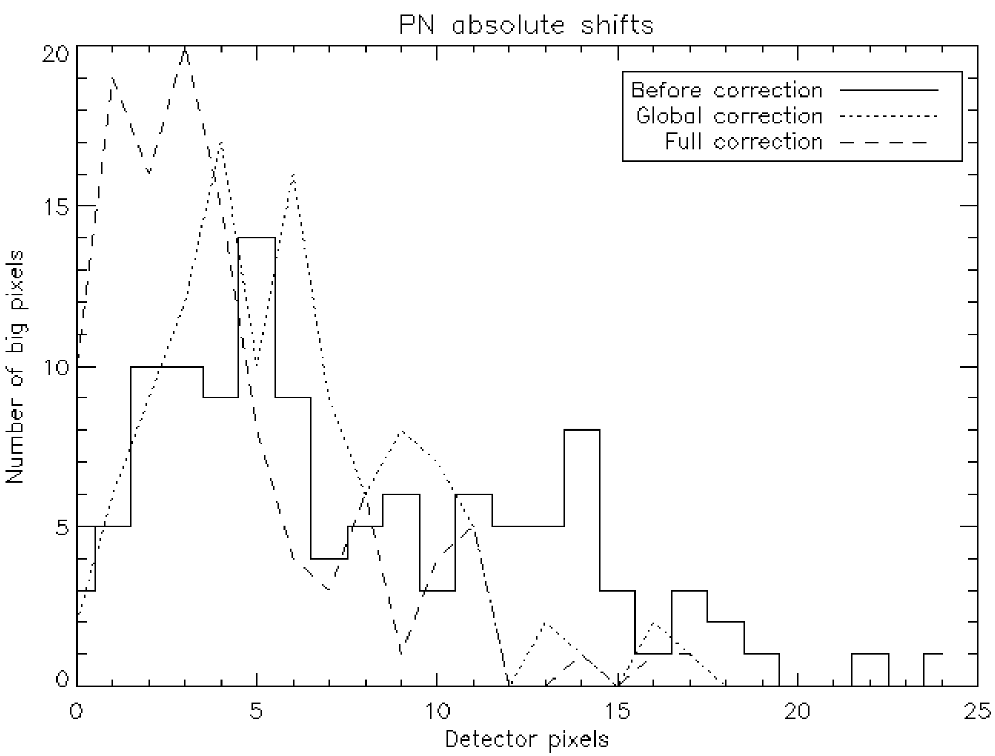
Improvement after PN correction

1. Improvement at focal plane level can be due to star tracker (except **scale**)
2. Further improvement **at CCD level** must be investigated
3. **Median absolute shift** PN: 6.7 ➔ 6.0 ➔ 3.4 det pixels
4. **PN χ^2** : 462/114 ➔ 274/110 ➔ 106/66



Best global transformation:

- **Scale factor**: –4.1 +/- 0.3 E-4 (0.4” or 13 µm at FOV edge)
- Rotation: –0.7 +/- 0.08 arcmin (0.2” or 6 µm at FOV edge)
- Shift: not significant

Individual CCDs: larger values, particularly CCD 12 (corner, only 100 sources). **PSF distorsion** instead?

Still to be done

1. Enter the new MOS CCD astrometry in the **CCF**. I don't know how to do this, but I hope the SOC can do it.
2. Use this new CCF to recompute the MOS event lists for (a subset of) Iris' observations; recompute the MOS source lists
3. Check that the resulting MOS source lists are aligned with PN
4. Recompute the source lists from all cameras together and check that the strange patterns have gone away
5. Enough data to test **hidden variables**. Which ones? Tried time (before/after cooling, and long term); nothing obvious
6. Look at CCD-level (or else) trends for PN with **more sources**. Is it possible to run source detection at camera level over all observations at the SOC?