Astromatic calibration of astronomical images in DESDM

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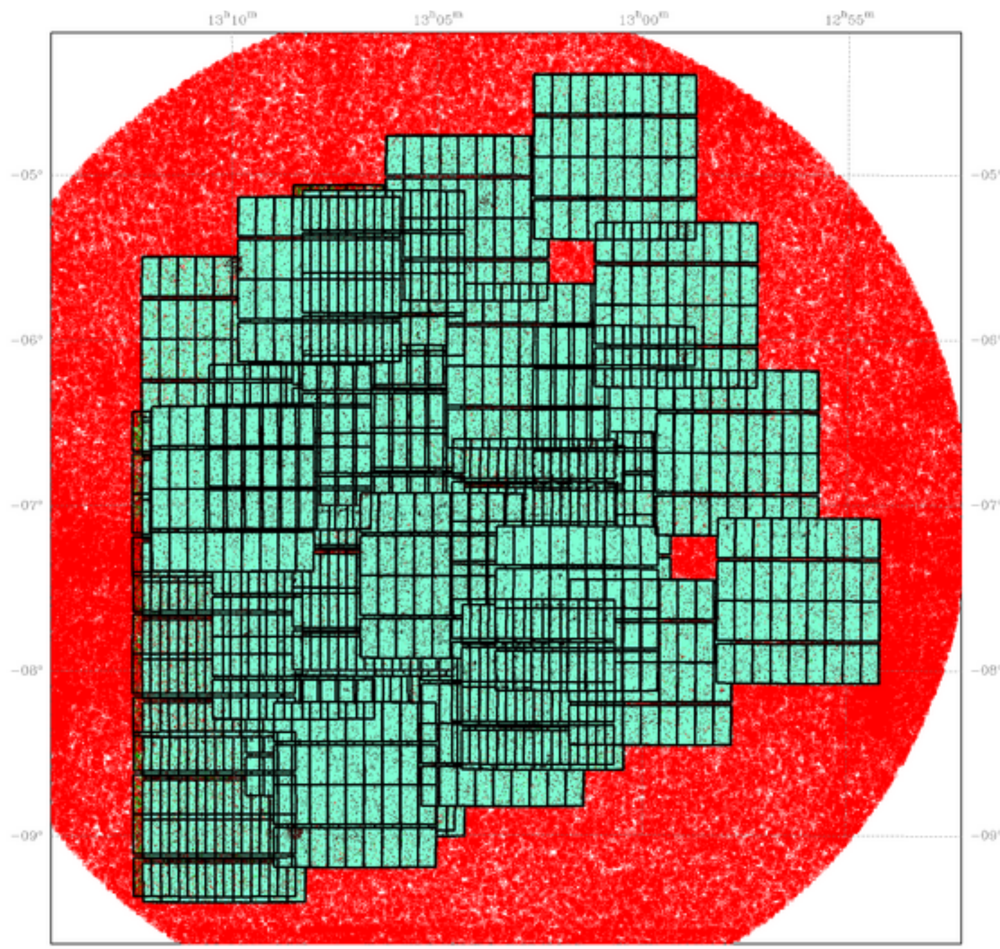
SCAMP

Automated astrometric calibration of astronomical images

- History
- Science requirements
- How positions are measured in SExtractor
  - what parameter to use
- SCAMP internals
  - matching of detections
  - global astrometry
  - astrometric reference catalogs
  - improving astrometric accuracy: DRC, proper motions
- Example of results
- SCAMP in the DESDM
  - specific issues
  - Built-in quality control and metadata output
  - Pending issues and forthcoming developments

History

- SCAMP was originally developed at TERAPIX to calibrate the CFHTLS, as a successor to Mario Radovich's Astrometrix. The CFHTLS:
  - >20TB of science image data
  - Each individual MEGACAM 300-600s exposure is a 1º mosaic of 36 CCD frames and contains about 10^4-10^6 detections.
  - ~580 sq.deg. covered in up to 5 bands
  - In a given region of the sky anything from 1 to 2000 exposures can overlap
  - Scientific goals required an accurate relative positioning of images (below 50 mas)
  - Astrometric and photometric calibrations had to accommodate various sky coverage strategies



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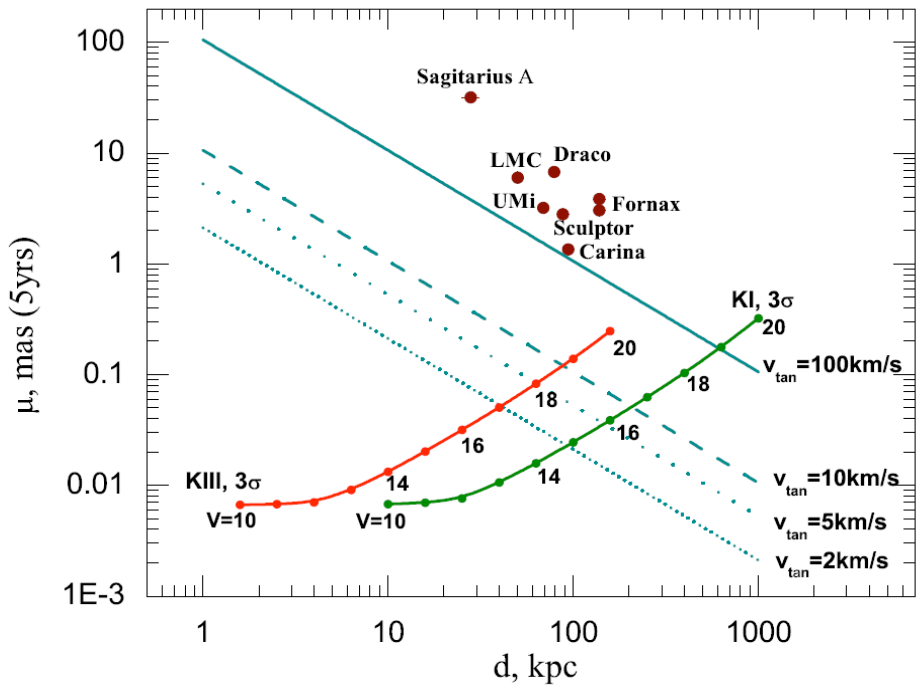
Astrometric requirements for contemporary science

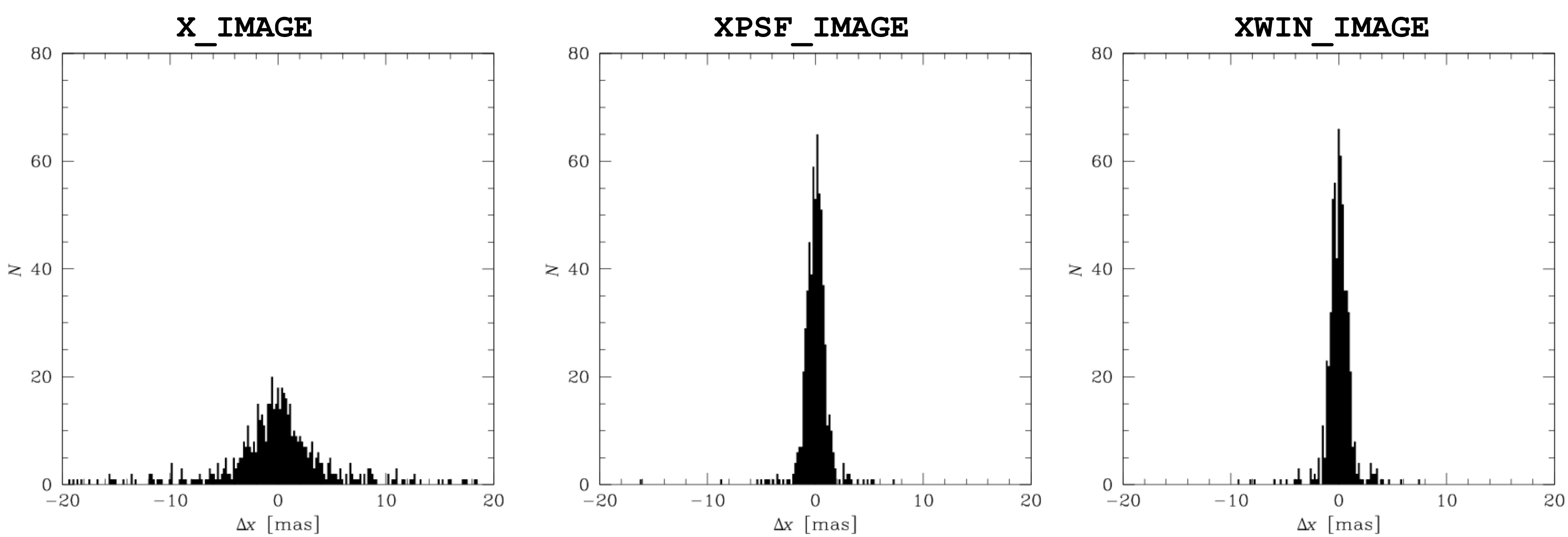
- Morphological analyses and weak lensing studies
  - Relative astrometry must be accurate to the level of <10% of the PSF FWHM.
- Galactic structure: proper motions
  - Relative positional accuracy over the field must be close to photon-noise limited
    - Good image sampling
    - Appropriate observing strategy
      - Low airmasses
      - Dithering strategy



Proper motion accuracy expected from a 5-year Gaia experiment (***Kucinskas et al. 2005***)

Centroid measurements

- Several centroiding procedures have been implemented in SExtractor:
  - **X_IMAGE,Y_IMAGE:** « isophotal » measurements are fast but their accuracy is poor
  - **XPSF_IMAGE, YPSF_IMAGE**: derived from PSF-fitting
  - **XMODEL_IMAGE, YMODEL_IMAGE**: derived from galaxy model-fitting
  - **XWIN_IMAGE, YWIN_IMAGE:** Gaussian-weighted centroiding:.
    - FWHM of the Gaussian set to twice the half-light radius
    - 5 iterations in average
    - Almost (within ~10%) as accurate as PSF-fitting on background-noise limited images, but much faster
    - Works well with galaxies



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Astrometry: automated pattern matching

- Associate detections with a reference catalogue like **GSC**, **USNO**, or **UCAC**.

- Direct matching techniques with invariance to scale, rotation, and translation
  - Search in “triangle space” (e.g. ***Groth et al. 1986***, ***Valdes et al. 1995***)
    - Brute-force approach: memory usage & computing time $\propto N^3$
      - practical limit is a few hundred stars
      - relies heavily on stellar magnitude ranking
    - A clever pre-selection of triangles can speed up processing by 1-2 orders of magnitudes (***Pál & Bakos 2006***)
  - Search in “quad-space”: **Astrometry.net** (***Hogg et al. 2008***)
    - Huge index in the form of a 4D KD-tree pre-computed on USNO-B+Tycho-2
    - Very fast on most images
    - Not in SCAMP because of licensing issues
  - **SCAMP** (***Bertin 2006***) approach: 3 steps
    - Find position angle and pixel scale using pairs of detections
    - Find coordinate shift using detections
    - Match based on Euclidean distance after applying scaling, rotation and shift.
    - Several thousands of sources can be cross-matched in a matter of seconds

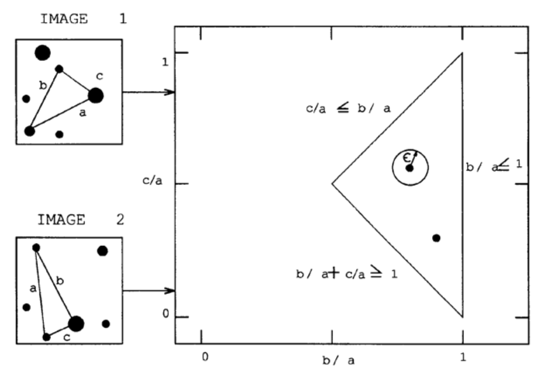
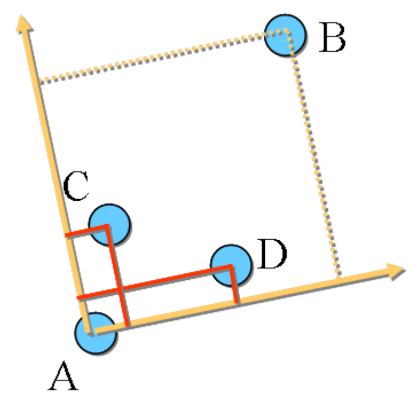


Fig. 1—Representation of triangles in *triangle space*. The lengths of the triangle sides are used to form the ratios b/a and c/a and these ratios define a two-dimensional space. Because of the ordering of the lengths the triangle coordinates will only occupy the indicated triangular region. Triangles from two images are matched when they are within a distance ϵ of each other in the triangle space.



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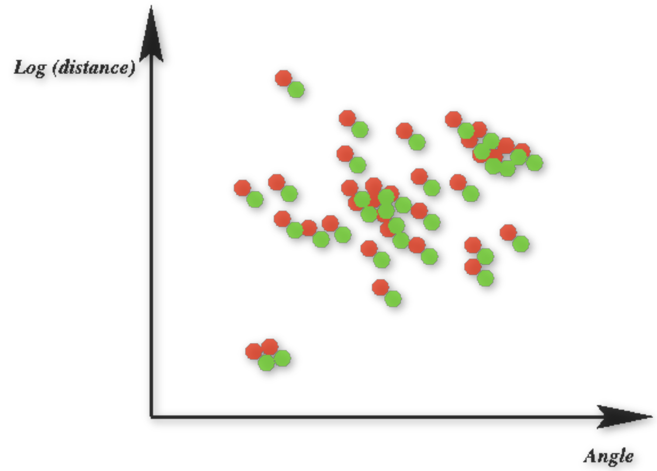
Astrometric matching: finding position angle and scale

- Match source pairs in the reference and extracted catalog in pos.angle-log(distance) space using bandpass-filtered cross-correlation (e.g. ***Kaiser et al. 1999***)
- Must pay attention to folding on the scale axis
- In general, a 7’×15’ image can be correctly oriented and scaled within a 1 sq.deg box.



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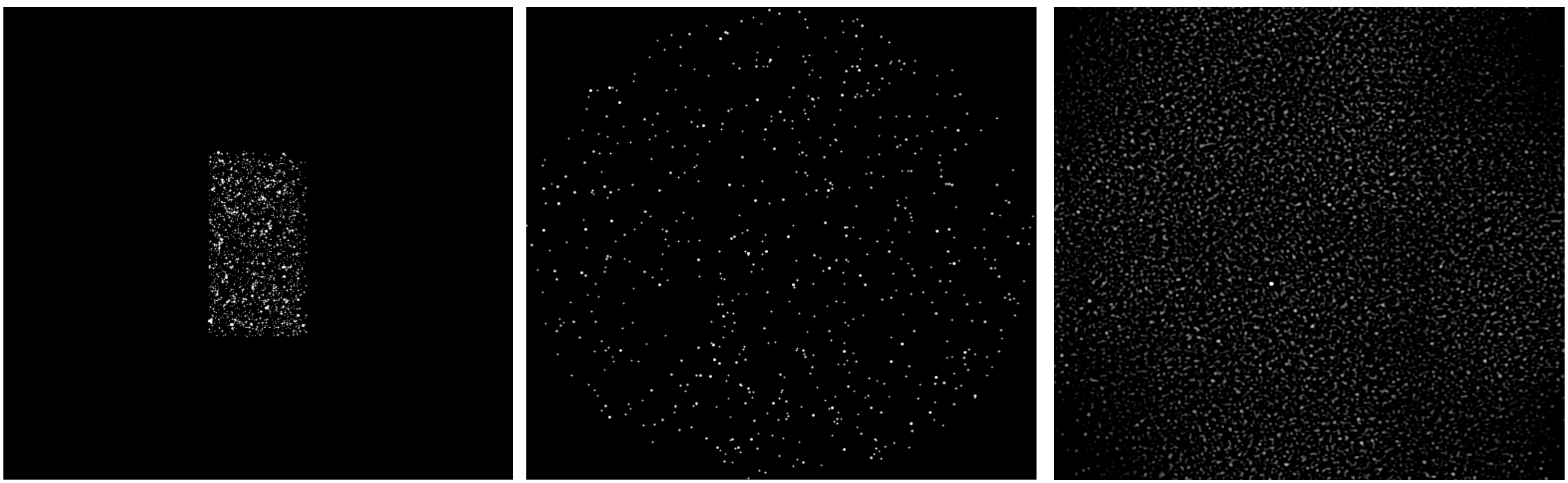
Astrometric matching: finding coordinate shift

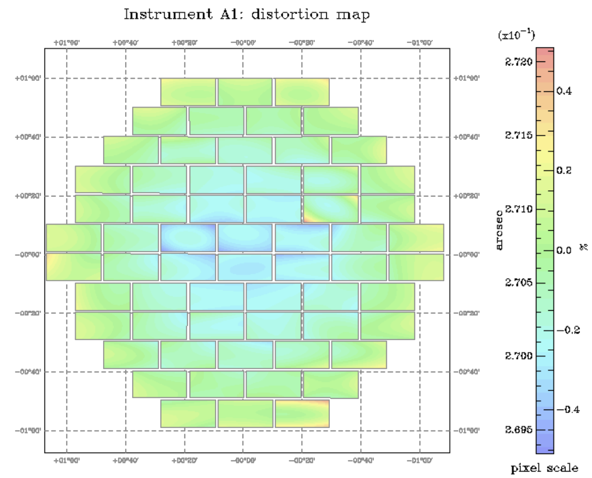
- Match source pairs in the reference and extracted catalog in projected coordinate space using cross-correlation
- Possible image flip
- Modulation due to source clustering and catalog boundaries must be minimized with data-windowing and bandpass-filtering
- Typically, a 7’×15’ image can be correctly positioned within a box of a few sq.deg.
- Slight improvement by adding magnitude dependency.

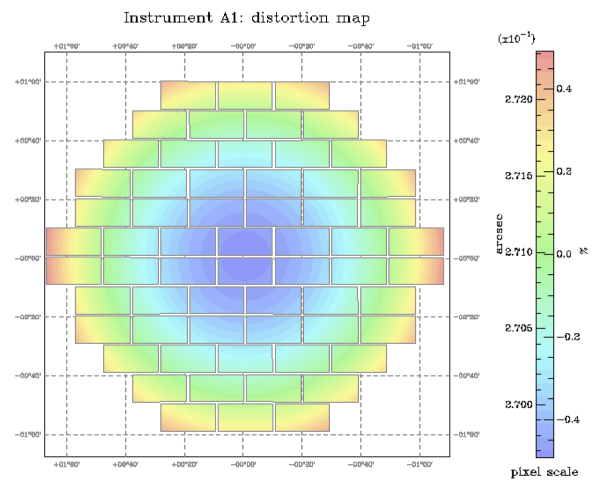


A global astrometric solution

- The mapping of astrometric distortions requires at least a 3[rd] order polynomial in projected coordinates ξ
  - 20 free parameters per CCD
  - Naive approach: fit the distortion coefficients for each exposure using a reference catalog (GSC, USNO,…)
    - Simple and fast but too sensitive to inaccuracies in the reference catalog, especially when a little more than 20 stars are cross-identified on a CCD.
  - Global solution: fit the distortion coefficients by additionally minimizing the distances between the projected coordinates of overlapping detections.
    - Approach taken for many astrometric reduction problems (e.g. ***Eichhorn 1960***, ***Deul et al. 1995***, ***Kaiser et al. 1999***, ***Radovich et al. 2004***)
    - Manages to reach a very good accuracy (close to the theoretical instrumental level)
    - For every source s on overlapping exposures *a* and *b* minimize

$$\chi^2 = \sum_s \sum_a \sum_b w_{sab} \left\| \xi_a(\boldsymbol{x}_{sa}) - \xi_b(\boldsymbol{x}_{sb}) \right\|^2$$





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Minimising the number of free parameters

- DECam: 62x20 = 1240 free parameters per exposure
  - Quickly leads to impractically large normal equation matrices
  - Iterative approach necessary
  - Too many free parameters: robustness problems arise because of a lack of sources or confusion in some fields
- For a given instrument (and a given filter combination), one may assume that the distortion pattern does not vary measurably over some period of time
  - We must allow the linear part of the distortion pattern to vary <u>globally</u> from exposure to exposure because of differential atmospheric refraction and flexures
  - $1240.n_{\text{instru}} + 6.(n_{\text{exp}} - n_{\text{instru}})$ free parameters
  - Requires an intermediary transformation to a common re-projection
    - stereographic projection chosen because it maps disks to disks.
    - Jacobians of the re-projections are involved

$$\begin{aligned}\frac{\partial\chi^2}{\partial c_{qf}} = \; & 2\sum_s\sum_a\sum_{b>a} w_{sab}\sum_d \Bigg(\xi^0_{ad}(\boldsymbol{x}_{sa}) - \xi^0_{bd}(\boldsymbol{x}_{sb}) + \\ & \sum_e \left(\frac{\partial\xi^0_{ad}}{\partial x_{ae}}\right)_{\boldsymbol{x}_{sa}} \left(\sum_p c_{pe}\phi_p(\boldsymbol{\chi}_{sa}) + \sum_m d_{ame}\psi_m(\boldsymbol{\chi}_{sa})\right) - \\ & \sum_e \left(\frac{\partial\xi^0_{bd}}{\partial x_{be}}\right)_{\boldsymbol{x}_{sb}} \left(\sum_p c_{pe}\phi_p(\boldsymbol{\chi}_{sb}) + \sum_m d_{bme}\psi_m(\boldsymbol{\chi}_{sb})\right)\Bigg) \times \\ & \left(\left(\frac{\partial\xi^0_{ad}}{\partial x_{af}}\right)_{\boldsymbol{x}_{sa}}\phi_q(\boldsymbol{\chi}_{sa}) - \left(\frac{\partial\xi^0_{bd}}{\partial x_{bf}}\right)_{\boldsymbol{x}_{sb}}\phi_q(\boldsymbol{\chi}_{sb})\right) = 0 \quad \forall\, q \le Q, f = 1,\end{aligned}$$

$$\begin{aligned}\frac{\partial\chi^2}{\partial d_{gnf}} = \; & 2\sum_s\sum_{b\neq g} w_{sgb}\sum_d \Bigg(\xi^0_{gd}(\boldsymbol{x}_{ga}) - \xi^0_{bd}(\boldsymbol{x}_{sb}) + \\ & \sum_e \left(\frac{\partial\xi^0_{gd}}{\partial x_{ge}}\right)_{\boldsymbol{x}_{sg}} \left(\sum_p c_{pe}\phi_p(\boldsymbol{\chi}_{sg}) + \sum_m d_{gme}\psi_m(\boldsymbol{\chi}_{sg})\right) - \\ & \sum_e \left(\frac{\partial\xi^0_{bd}}{\partial x_{be}}\right)_{\boldsymbol{x}_{sb}} \left(\sum_p c_{pe}\phi_p(\boldsymbol{\chi}_{sb}) + \sum_m d_{bme}\psi_m(\boldsymbol{\chi}_{sb})\right)\Bigg) \times \\ & \left(\frac{\partial\xi^0_{gd}}{\partial x_{gf}}\right)_{\boldsymbol{x}_{sg}}\psi_n(\boldsymbol{\chi}_{sg}) = 0 \quad \forall\, g, n \le N, f = 1, 2,\end{aligned}$$

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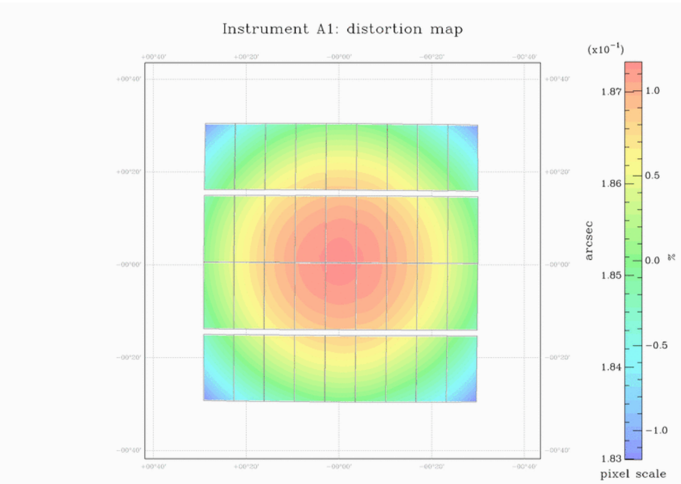
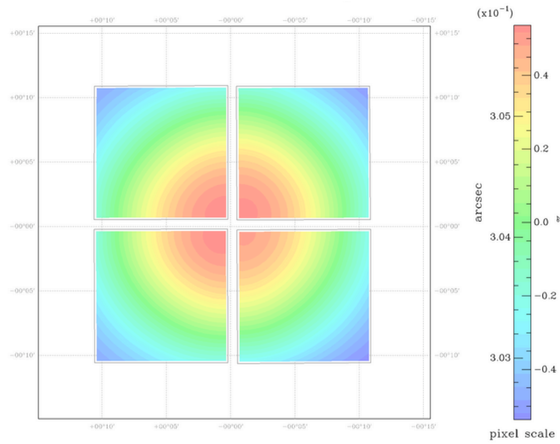
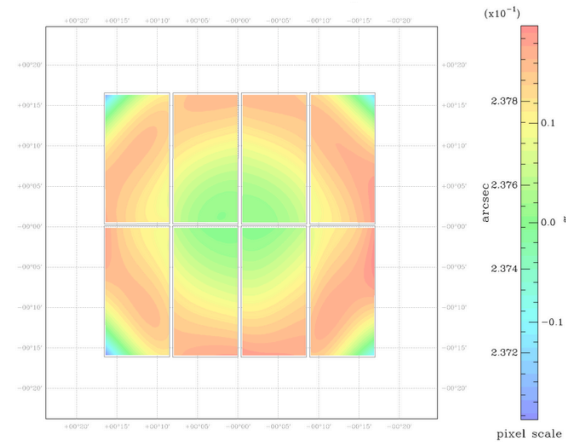
Distortion patterns of some existing wide-field instruments derived with SCAMP



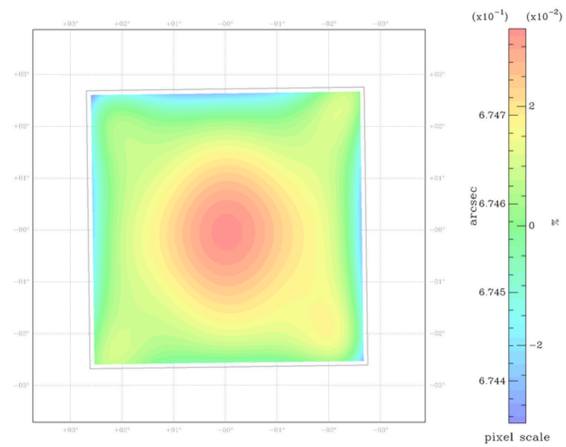
MEGACAM@CFHT-3.6m



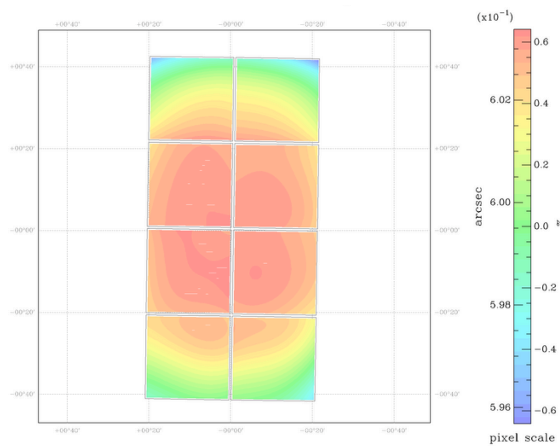
WIRCAM@CFHT-3.6m



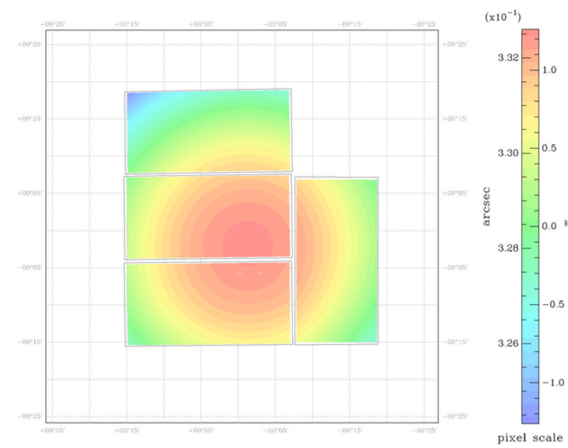
WFI@ESO-2.2m



ESO-Schmidt-plate@CAI



EROS_R@Marly-1m



WFC@INT-2.5m

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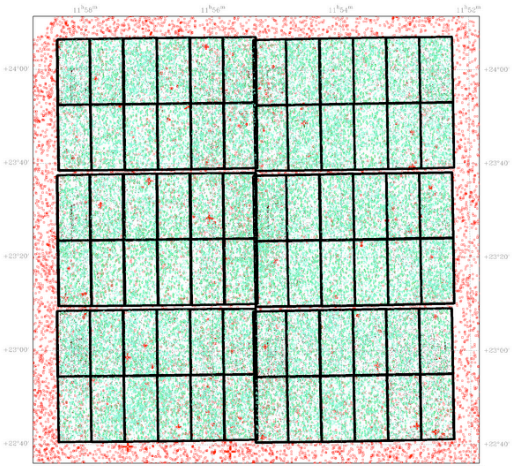
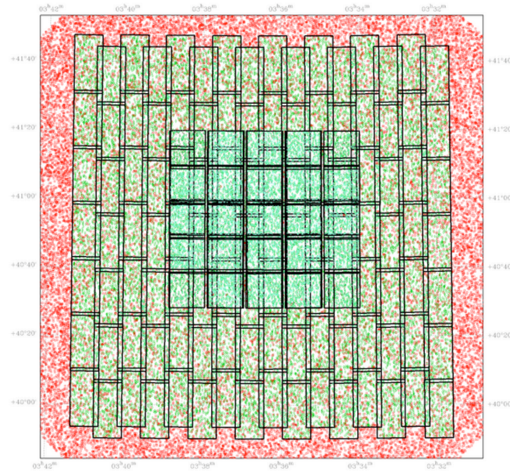
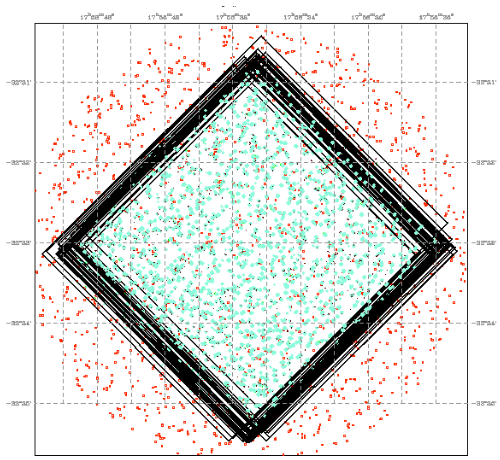
SCAMP can compute astrometric solutions for arbitrary survey/instrument geometries/ histories and several overlapping instruments simultaneously



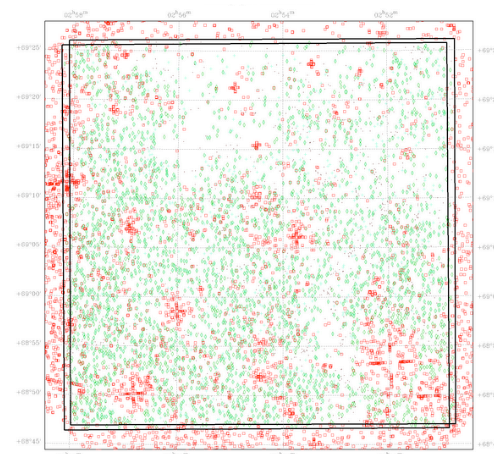
CFH12k



WIRCAM+2MASS

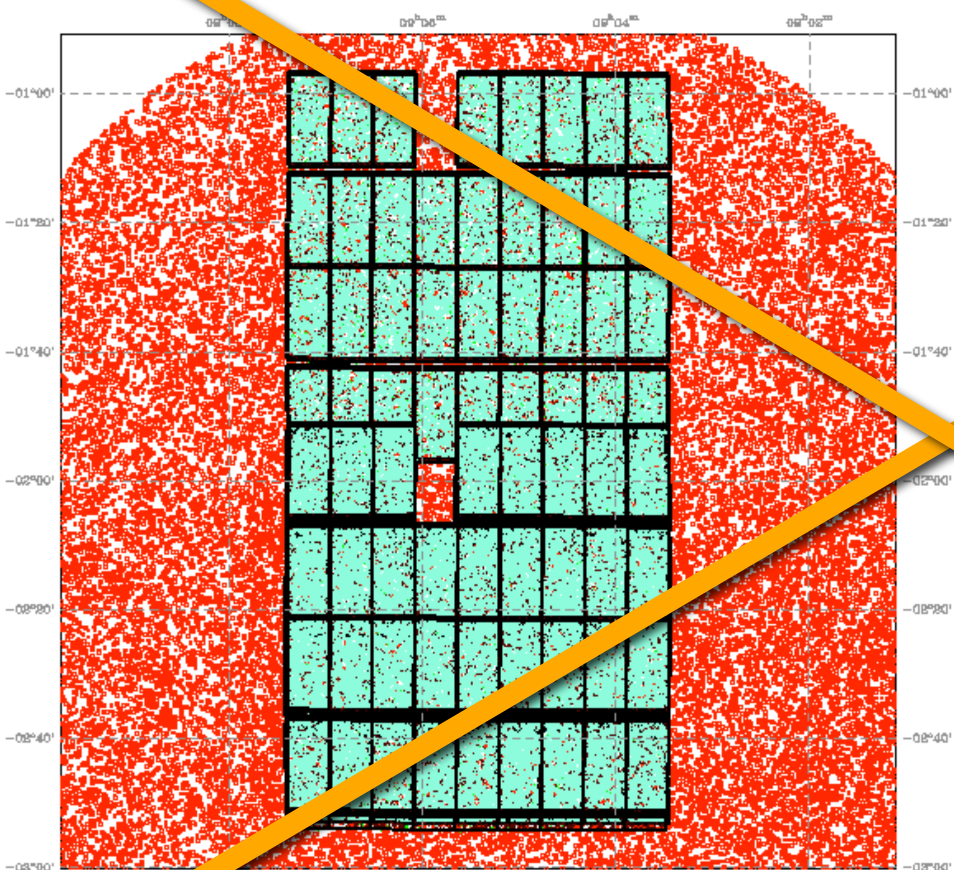


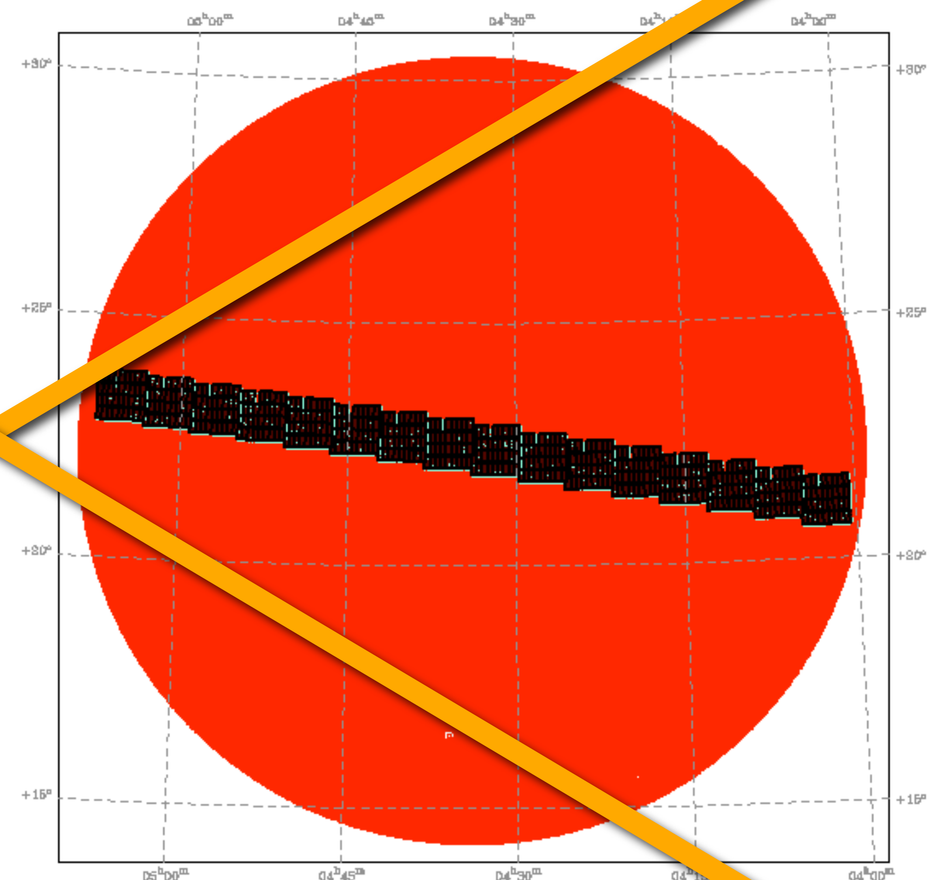
Planet



Pair of Tautenburg Schmidt plates

Astrometry: bad observing strategies ✪

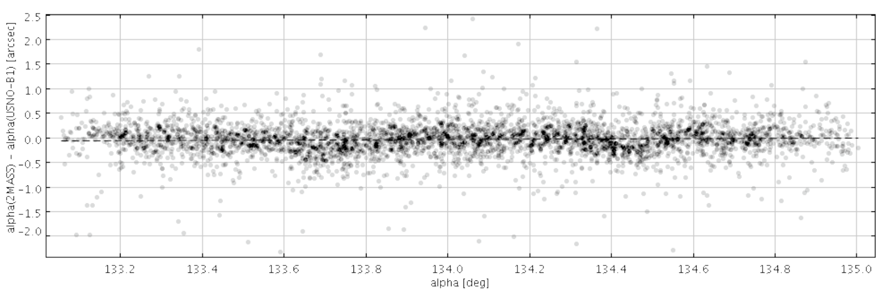


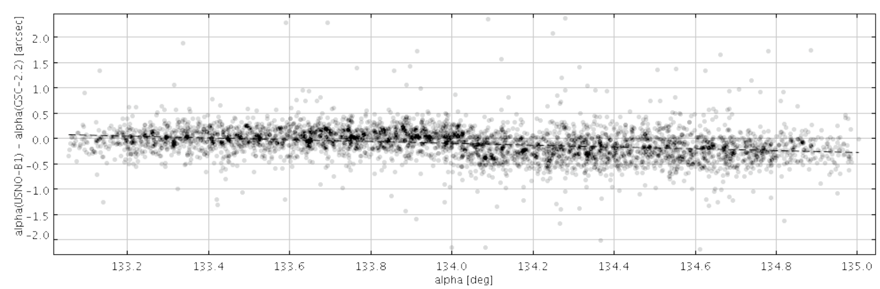


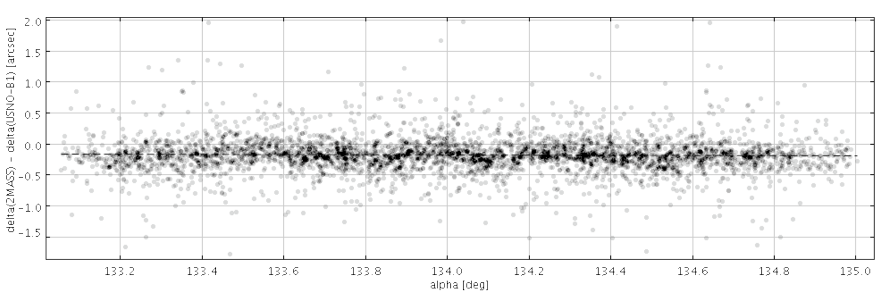
Astrometric reference catalogs

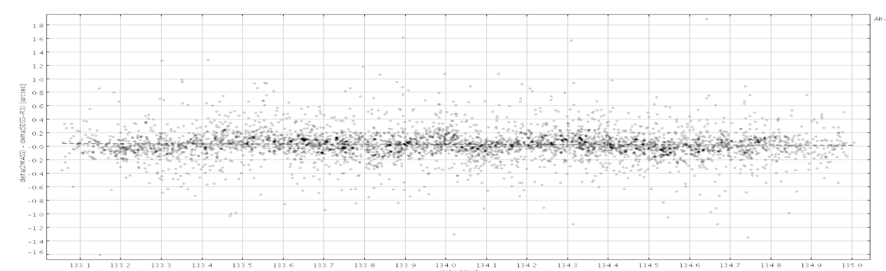
- Systematic offsets of ~0.2-0.3” are commonly found between astrometric reference catalogs on scales of 0.1-1 degree
- Amongst existing deep all-sky catalogues, 2MASS seems the most reliable.
  - confirmed by several SCAMP users and others
- UCAC-3 is the best catalog for shallower surveys

Code	Real name	Coverage	Density[a]	Bands	Mag. limit	$\sigma_{\mathrm{pos.}}$[b]	System[c]	Epochs[d]	Proper motions
GSC-1.3	Guide-Star Catalog ACT V1.3[e]	All sky	610	V	$V \approx 15.5$	0.3”	FK5	1975-1988	
GSC-2.2	Guide-Star Catalog ACT V2.2.1[f]	All sky	11050	B_J, V, R_F, I_N	$B_J = 19.5$	0.3”	ICRS	1975-2000	
GSC-2.3	Guide-Star Catalog ACT V2.3.2[g]	All sky	22920	U, B, B_J, V, R_F, I_N	$B_J = 21.5$	0.3”	ICRS	1975-2000	✓
USNO-A1	PMM US Naval Observatory A1.0[h]	All sky	11830	B_J, R_F	$B_J \approx 19.5$	0.3”	FK5	1949-1990	
USNO-A2	PMM US Naval Observatory A2.0[i]	All sky	12760	B_J, R_F	$B_J \approx 19.5$	0.3”	ICRS	1949-1990	
USNO-B1	US Naval Observatory B1.0[j]	All sky	25350	B_J, R_F, I_N	$B_J \approx 21$	0.3”	ICRS	1949-2002	✓
UCAC-1	1st USNO CCD Astrograph Catalog[k]	$\delta \leq -15°$	≈ 1500	R_U	$R_U = 16$	70 mas	ICRS	1998-1999	✓
UCAC-2	2nd USNO CCD Astrograph Catalog[l]	$\delta \leq +40°$	≈ 1500	R_U	$R_U = 16$	70 mas	ICRS	1998-2002	✓
UCAC-3	3rd USNO CCD Astrograph Catalog[m]	All sky	2440	R_U	$R_U \approx 16.3$	70 mas	ICRS	1980-2002	✓
NOMAD-1	Naval Obs. Merged Astrom. Dataset[n]	All sky	27090	B, V, R, J, H, K_s	$B \approx 21$	0.3”	ICRS	1949-2002	✓
PPMX	Position and Proper Motions eXtended[o]	All sky	440	$B, V, R_U, R_F, J, H, K_s$	$R_f \approx 15.2$	40 mas	ICRS	1975-2002	✓
2MASS	2-Micron All Sky Survey point source[p]	All sky	11420	J, H, K_s	$J = 17.1$	0.2”	ICRS	1997-2000	
DENIS-3	DEep Near Infrared Survey version 3[q]	$\delta < +2°$	21270	i, J, K_s	$i \approx 18.5$	0.2”	ICRS	1996-2001	
SDSS-R3	Sloan Digital Sky Survey release 3[r]	5282 deg^2	27660	u, g, r, i, z	$r = 22.2$	80 mas	ICRS	2000-2003	
SDSS-R5	Sloan Digital Sky Survey release 5[s]	8000 deg^2	26880	u, g, r, i, z	$r = 22.2$	50 mas	ICRS	2000-2005	
SDSS-R6	Sloan Digital Sky Survey release 6[t]	9600 deg^2	29950	u, g, r, i, z	$r = 22.2$	50 mas	ICRS	2000-2006	
SDSS-R7	Sloan Digital Sky Survey release 7[u]	11700 deg^2	30610	u, g, r, i, z	$r = 22.2$	50 mas	ICRS	2000-2008	



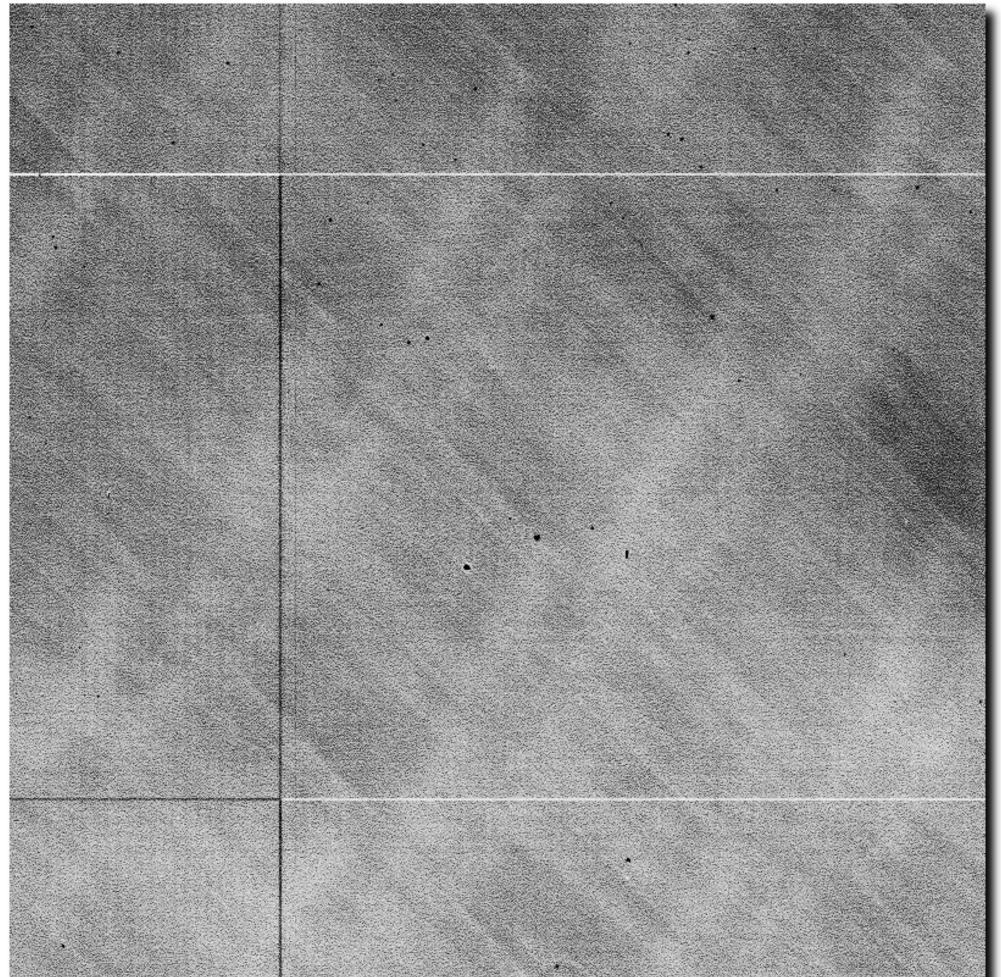






Astrometry: improving accuracy

- Intrinsic sources of astrometric errors
  - Variability of the intra-pixel response profile from pixel to pixel
    - Mostly affect IR arrays
    - On modern CCDs, repeatability of centroiding with properly sampled stars is ~ 1/300th of a pixel over the array (e.g. ***Yano et al. 2004***)
  - Step-and-repeat pixel size error on some large CCDs (***Shaklan & Pravdo 1994***): typically 0.5μm (a few hundredth of a pixel) each 512 or 1024 pixel
    - Equivalent to a few mas
    - MEGACAM CCDs did not have this problem
- Differential Chromatic Refraction
  - Atmospheric
  - Chromatic aberrations
- For large time intervals between exposures, one may leave source proper motions and parallaxes as free parameters (e.g. ***Eichhorn & Russell 1976***)



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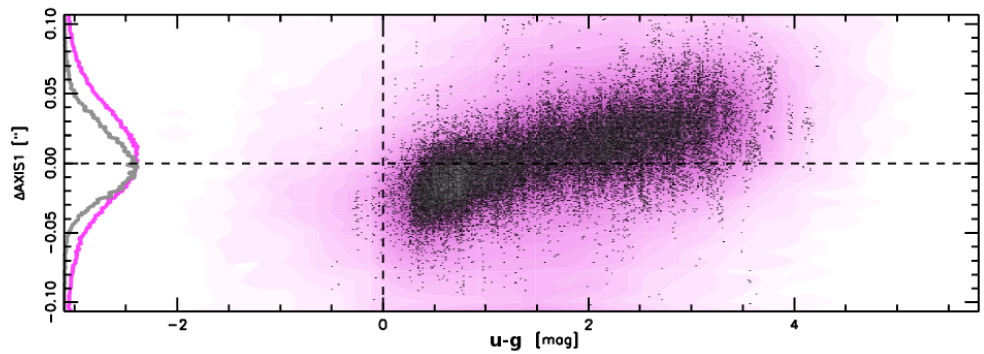
Differential Chromatic Refraction

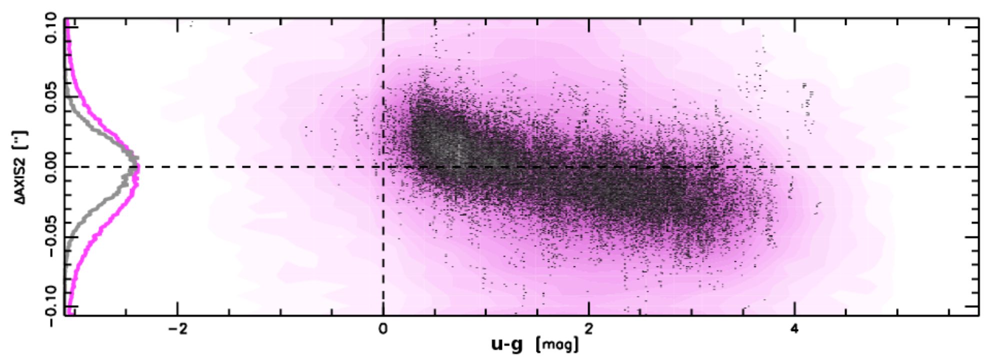
- For a star with spectral index α, observed at zenithal distance *z* in a filter of bandwidth *w* (in microns) centered on wavelength λ_0 (in arcsec):

$$\Delta z_{\lambda_0,w} \approx 23750 \left(\frac{dn}{d\lambda}\right)_{\lambda_0} \tan z \;\; w^2 \alpha$$

- w≈0.1μm for the u,g,r,i,z photometric system (SDSS,CFHTLS,…)
  - At *z*=45 deg, Δz varies from ~20mas (z band) to ~150mas (u band).
- <u>Most all-sky catalogues are not corrected for DCR!</u>
- Correction for differential chromatic refraction available in SCAMP
  - 2 different photometric instruments are required at least
  - Available in the merged catalogue output from SCAMP

$\Delta\alpha$ and $\Delta\delta$ as a function of u-g at airmass ~1.5





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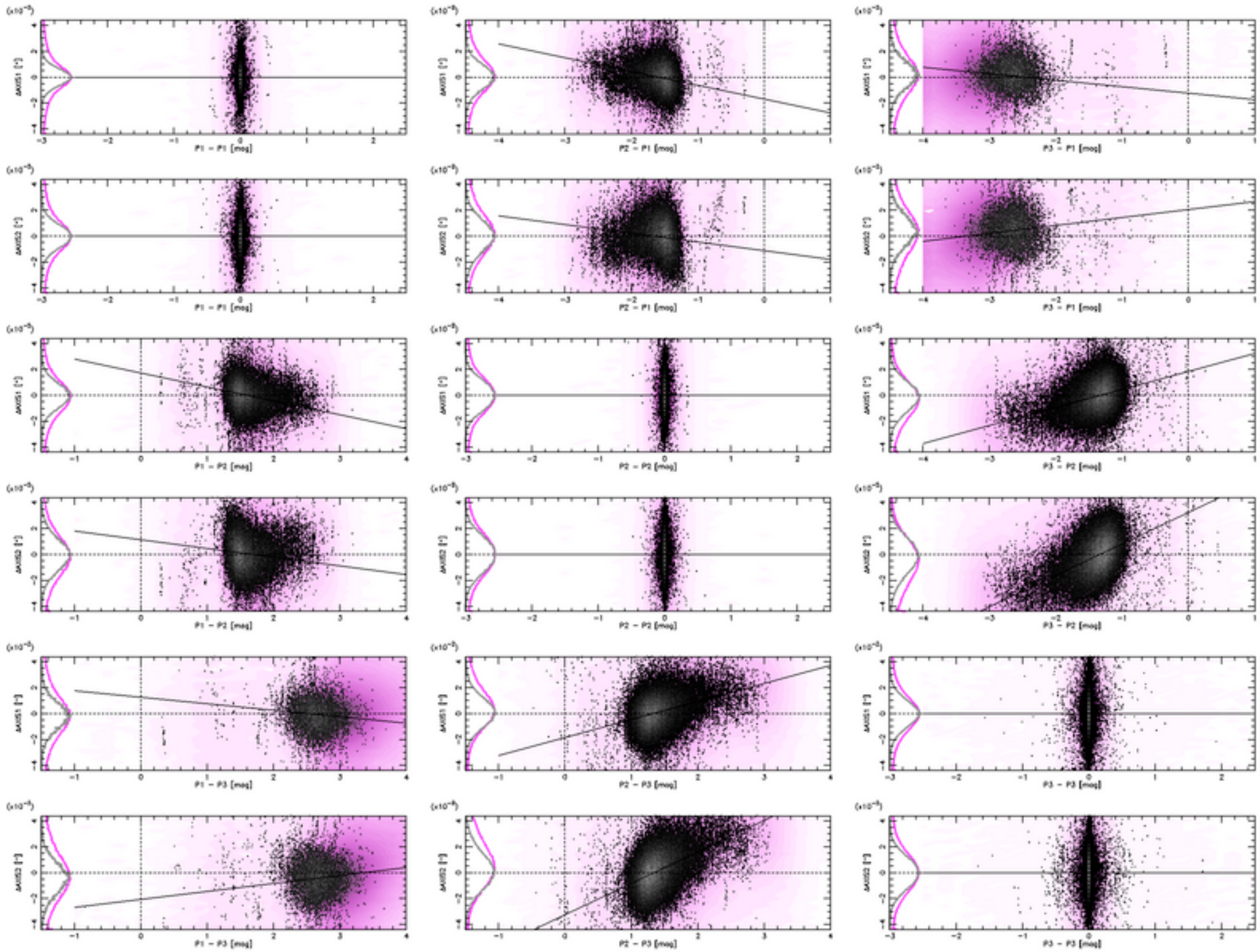
Differential Chromatic Refraction matrix in u,g,i



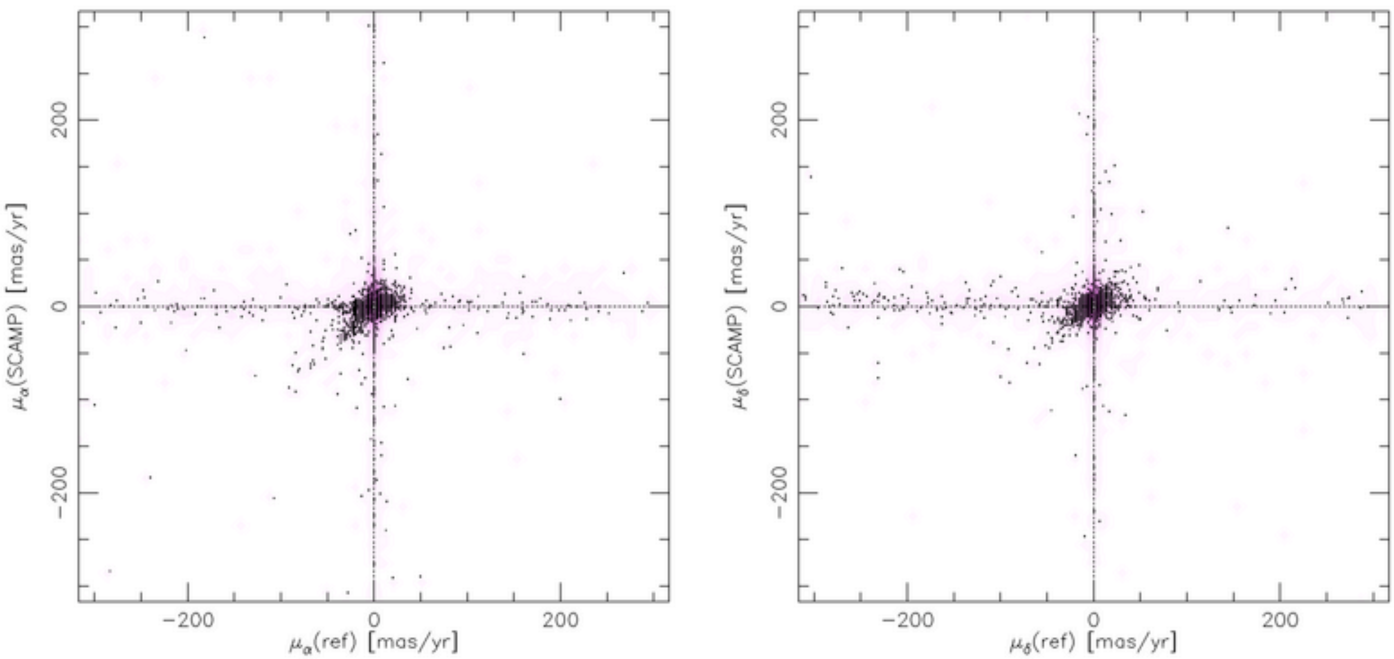
DARK ENERGY SURVEY

SCAMP

Proper motions

- Proper motion estimates
  - Linear regression over Julian dates
  - At least 2 different epochs are required
  - Most proper motion measurements >50 mas/yr in USNO-B1 catalog appear to be spurious
- SCAMP does not update the position of reference sources to the epoch of observations
  - Proper motions of stars with V>16 found in most all-sky catalogs are not reliable
  - The impact on calibration could easily be checked since a large fraction of faint sources are actually galaxies (fixed positions in the ICRS)

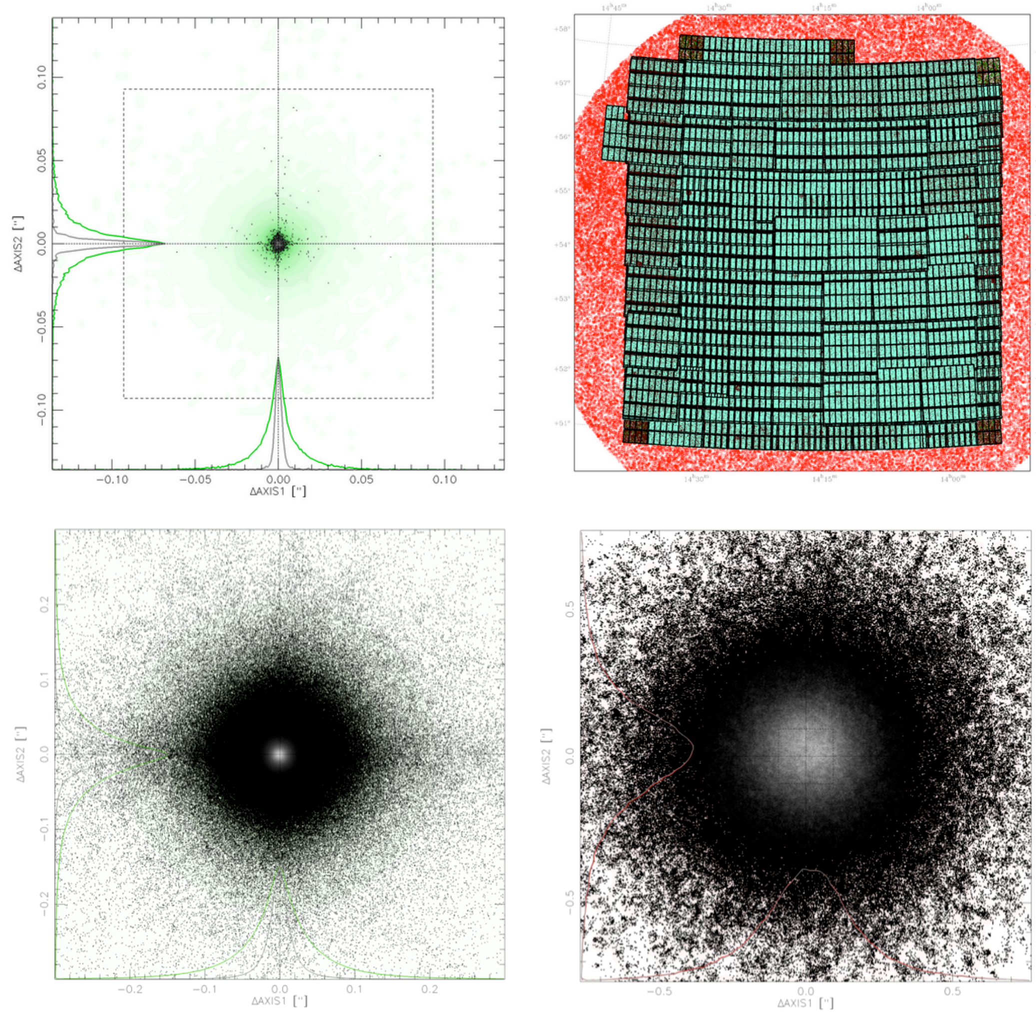
Comparison with USNO-B1 proper motions (abcissa): 20 D3 exposures in r over a period of 15 months (ordinates)



SCAMP

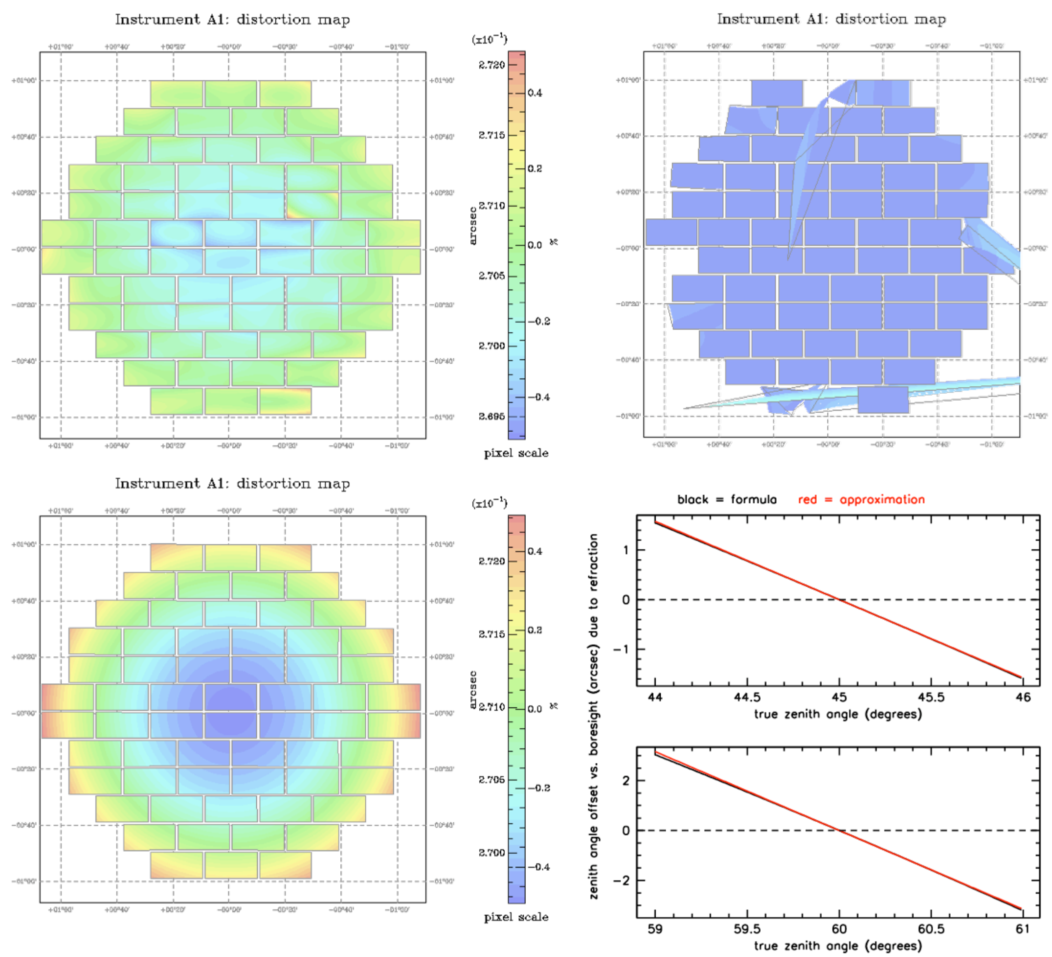
Example a very large astrometric calibration run:
1500 MEGACAM exposures from CFHTLS wide

- Accuracy
  - Internal residuals down to ~5 mas *rms* for uncrowded, high S/N sources in selected 300s CFHTLS exposures (χ^2/d.o.f. ~2). 20 mas *rms* is a more typical value for large numbers of exposures (20.10^6 sources, half of which are galaxies).
  - Residuals with respect to
    - 2MASS ~ 250 mas *rms*
    - SDSS ~ 40 mas *rms*
  - A large-scale (~10') residual distortion component variable from exposure to exposure can often be noticed at the level of a few mas RMS
    - Anomalous refraction?
- Speed
  - Based on FFTW, BLAS/LAPack
  - Multi-threaded
  - Efficient cross-identification engine
  - 2-10,000 sources/s on a quad-core CPU@3.0 GHz
  - Memory footprint: 200 bytes / detection



SCAMP in the DESDM

- SCAMP (astrometric reduction) is not operated in the way it was originally meant to
    - One solution per single exposure and per CCD, instead of a global solution that involves multiple exposures
    - Fix: assume that a stable, global solution exists for all CCDs (for the night, or the run), and adjust only low order terms over the whole mosaic.
        - stupidly, such an approach had not been planned while designing the software
        - currently using a “trick” by providing an additional mock catalog centered at RA,dec=0,0. The mock catalog is has the desired distortion pattern,very low errors, and therefore “drives” the global solution



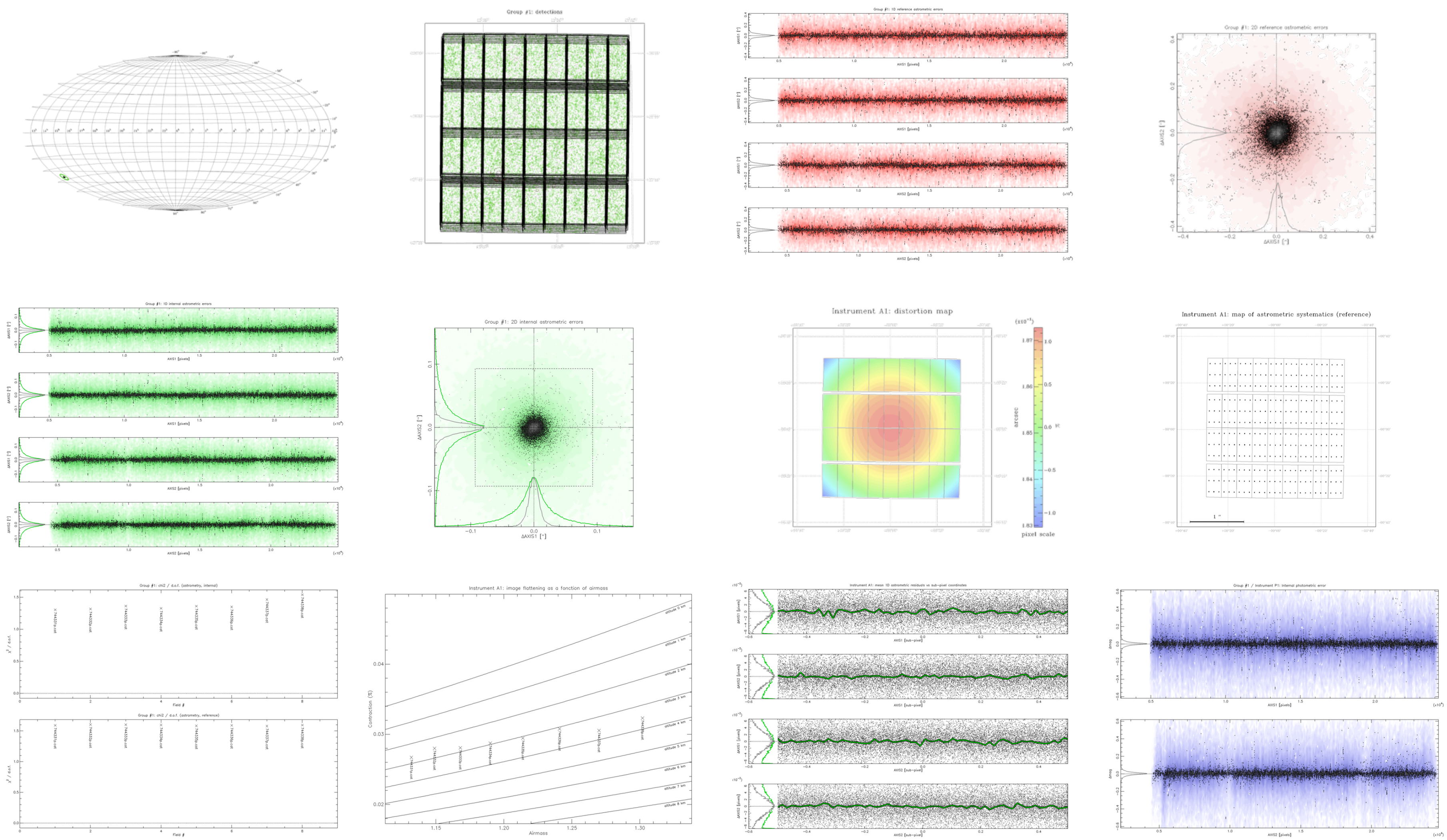
DARK ENERGY SURVEY

SCAMP

Built-in quality control and metadata

- SCAMP runs a variety of diagnostics
  - Various scatter plots and 2D histograms are produced
  - Numbers are written to a metadata file in XML-VOTable format at the end of each run.
    - An XSLT stylesheet that translates to HTML comes with the SCAMP package.
    - High level libraries such as vo.table for Python can be used to parse the VOTable
      - there are a few stability and compliancy issues (can easily be fixed)
    - More information at Astromatic.net

Built-in quality control (cont.)



SCAMP

Pending issues and future improvements

- Improvements to SCAMP
  - Implement a specific operating mode to restrict the solution to global focal-plane parameters
    - at least up to low-order polynomial terms
  - Solve the issue of excessive residuals in RA after calibration of simulations based on TRILEGAL proper motions
    - Proper motions in current deep all-sky reference catalogs can't be used (unreliable)
    - Would have to derive proper motions by ourselves (SCAMP can already do that)
      - Would need at least two observations at one year interval, each in at least two bands (to correct for DCR)
    - Are we sure that the simulated proper motions have to right amplitude?
  - Add compliancy with the most recent WCS prescriptions for describing distorsion patterns