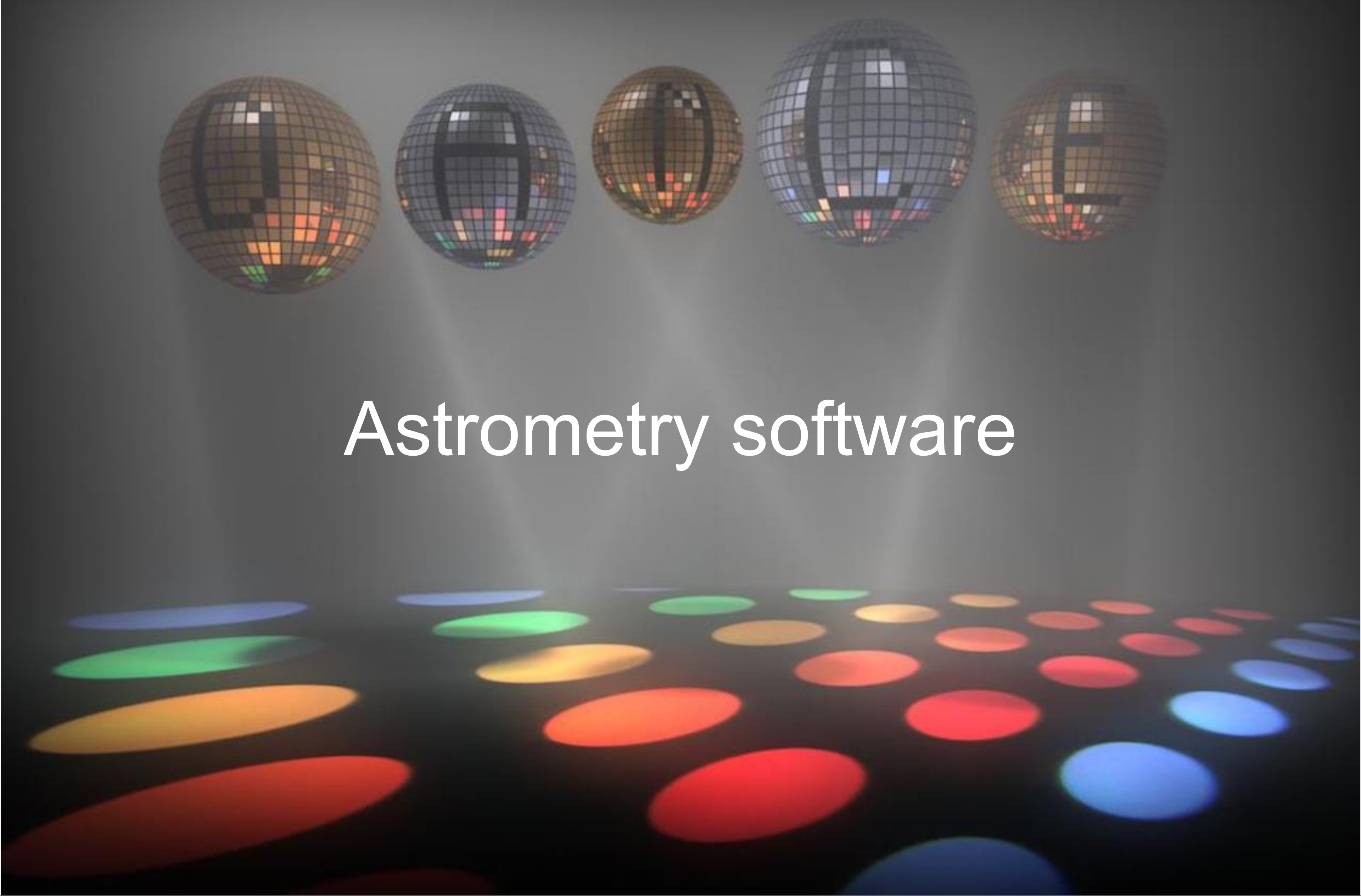
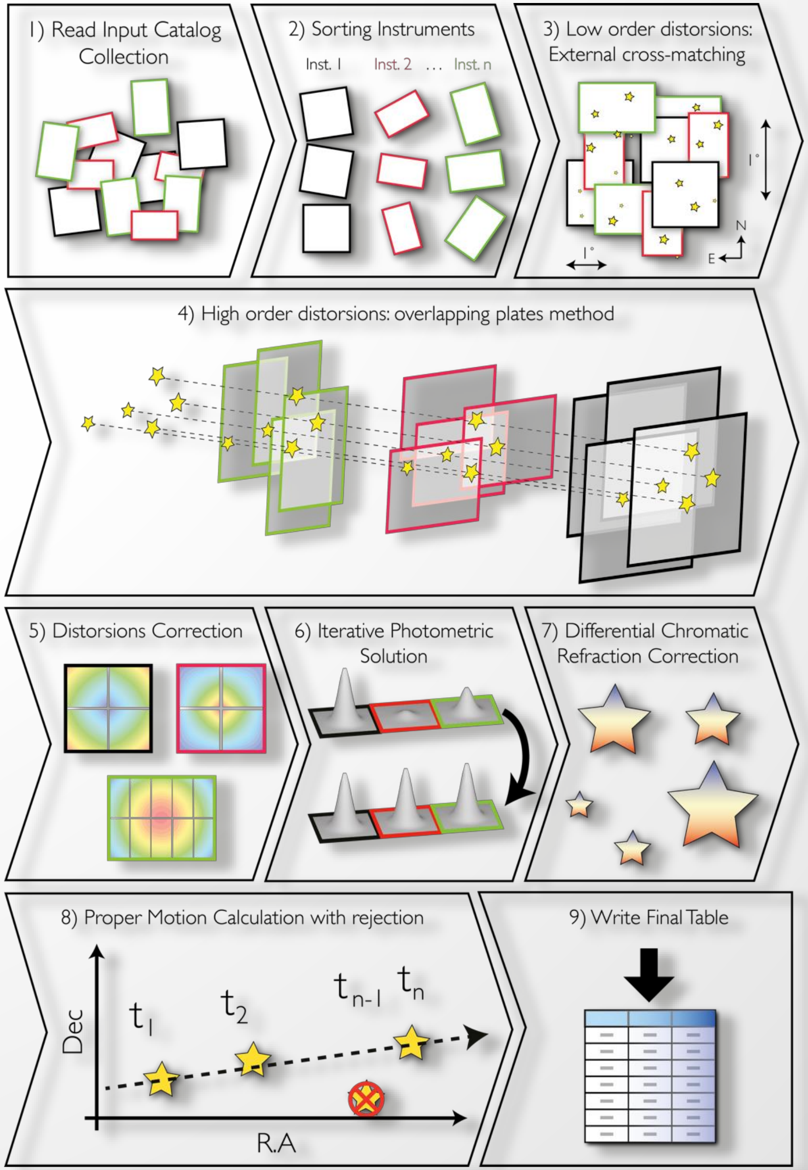


Astrometry software

Emmanuel Bertin (IAP)

SCAMP overview

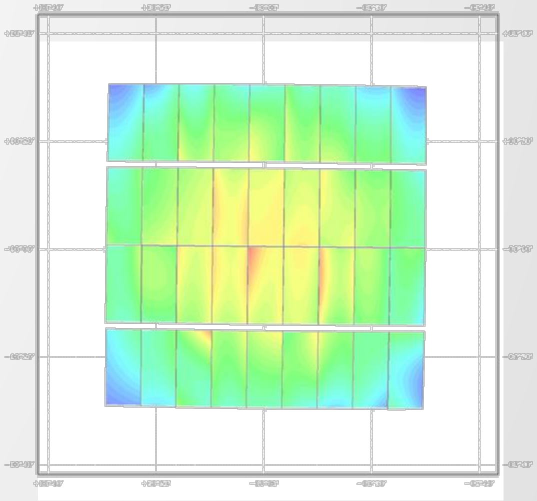


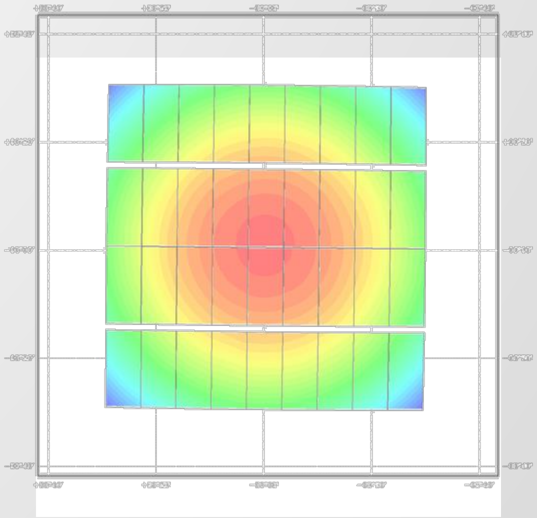
Courtesy Hervé Bouy

A global astrometric solution

- The mapping of astrometric distortions typically requires a 4th degree polynomial in projected coordinates ξ
  - 30 free parameters per CCD, written to FITS headers using the "TPV" convention
  - Approaches that don't work :
    - "physical" modeling (CCD geometry, optical distortions, atmospheric refraction)
    - fit the distortion coefficients for each exposure using a reference catalog (GSC, USNO,…)
  - Global solution: fit the distorsion coefficients by additionally minimizing the distances between the projected coordinates of overlapping detections.
    - ***Eichhorn 1960***, ***Deul et al. 1995***, ***Kaiser et al. 1999***, ***Radovich et al. 2004***)
    - For every source s on overlapping exposures *a* and *b* minimize

$$\chi^2 = \sum_s \sum_a \sum_b w_{s,a,b} \left\| \boldsymbol{\xi}_a(\boldsymbol{x}_{s,a}) - \boldsymbol{\xi}_b(\boldsymbol{x}_{s,b}) \right\|^2$$





Minimizing the number of free parameters

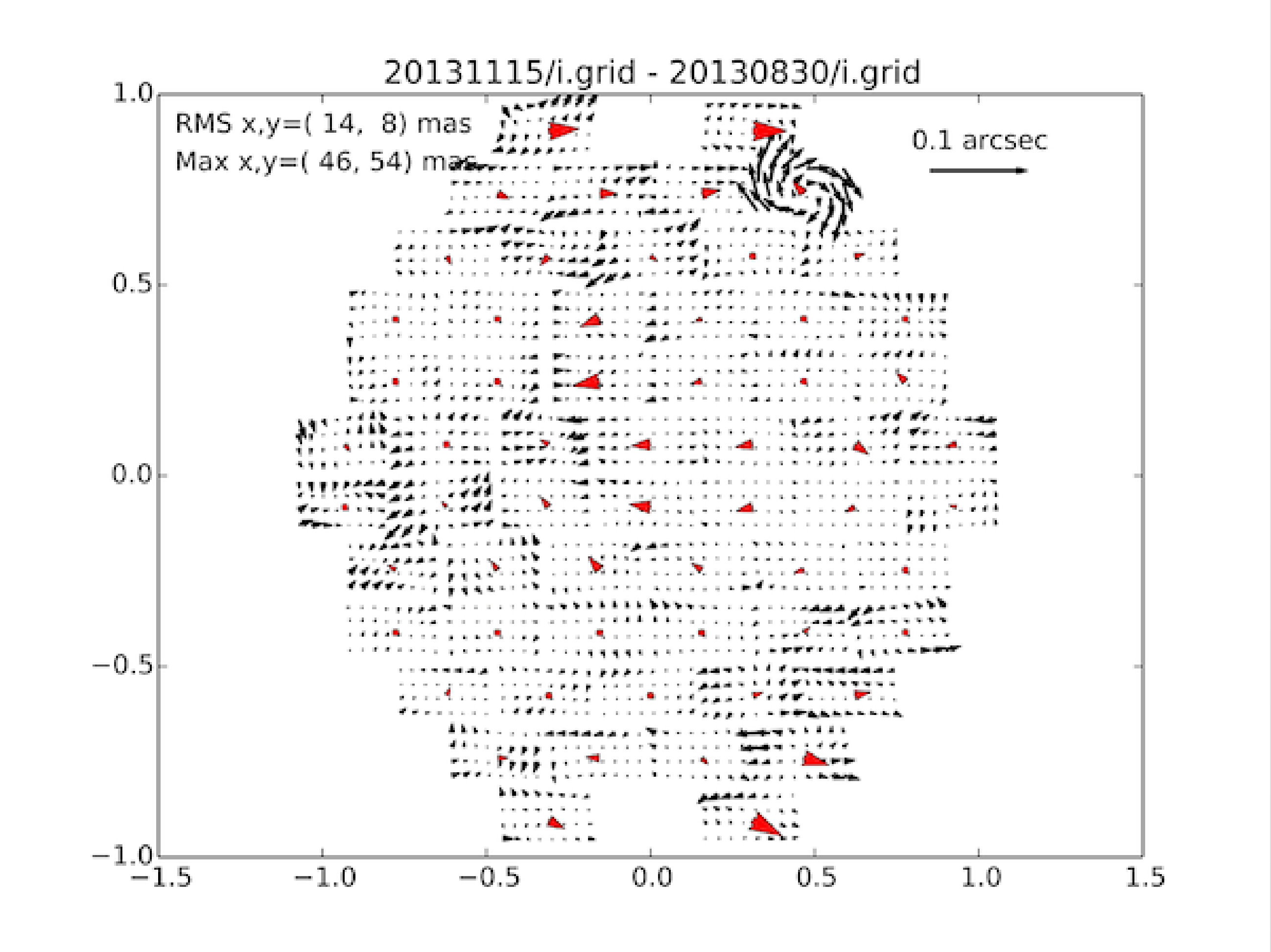
- Mosaic cameras: $n_{\text{chip}}\times 30$ = hundreds of free parameters per exposure for a 4$^{\text{th}}$ degree polynomial per chip!
  - Too many free parameters: robustness problems arise because of a lack of sources or confusion in some fields
- For a given instrument (and a given filter combination), one may assume that the distortion pattern does not vary measurably over some period of time (observing run)
  - Use FITS keywords to automatize the process of grouping exposures per instrumental "context"
- One must still allow the lower orders of the distorsion pattern to vary <u>globally</u> from exposure to exposure because of atmospheric refraction and flexures

$$\boldsymbol{\xi}_{c,e} = \boldsymbol{\xi}^0_{c,e}\left(\boldsymbol{x} + \sum_p \boldsymbol{f}_{c,i,p}\phi_p(\boldsymbol{x}) + \sum_m \boldsymbol{g}_{e,m}\psi_m(\boldsymbol{\rho})\right)$$

  - $n_{\text{chip}}\times n_{\text{instru}}\times 30 + 12\times(n_{\text{exp}} - n_{\text{instru}})$ free parameters if changes from exposure to exposure are described using a 2$^{\text{nd}}$ degree polynomial
  - Requires an intermediary transformation to a common re-projection
    - Deal with the Jacobians of individual re-projections

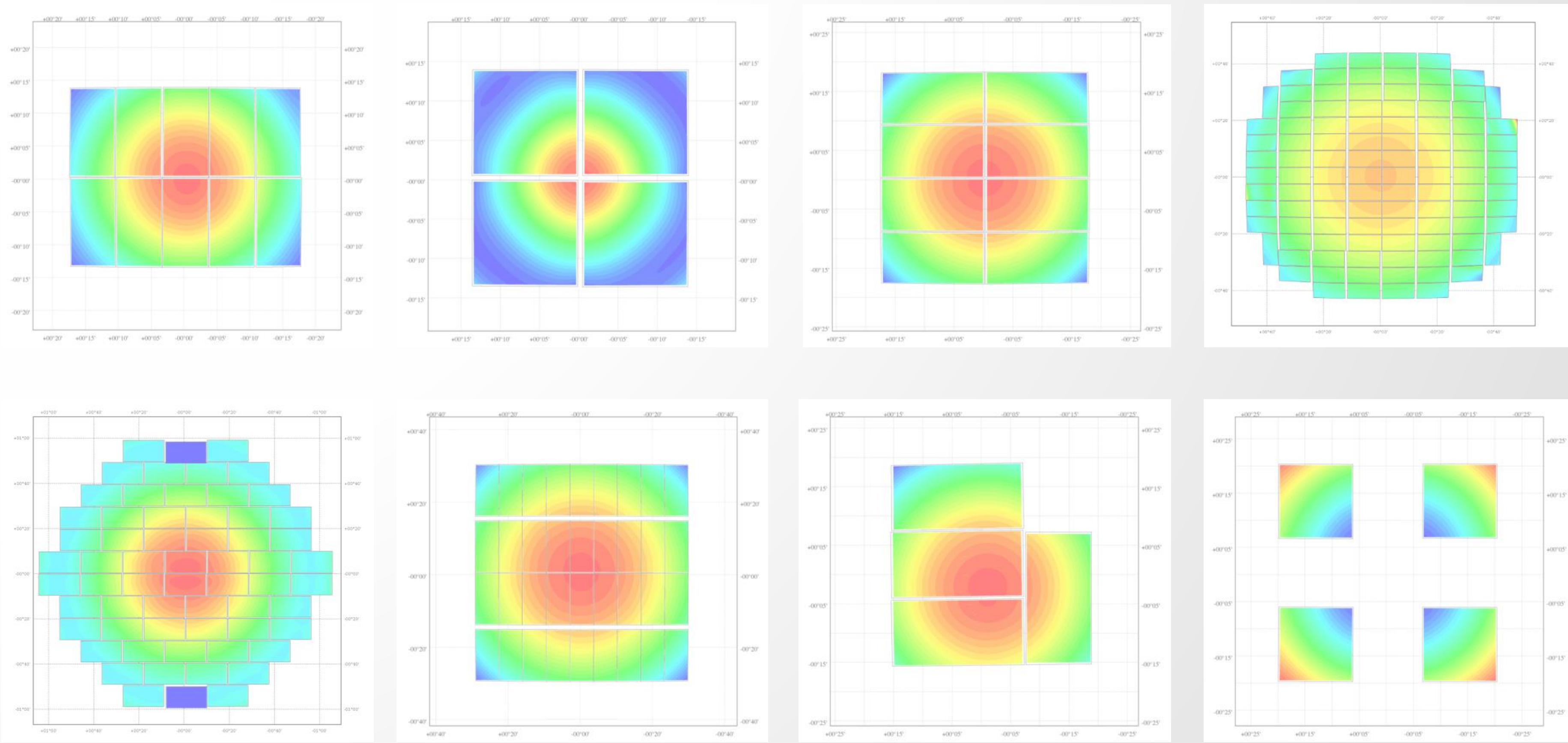
How stable are wide-field instruments?

- Filter change
- Time + Camera warm-up



courtesy of G.Bernstein, DES

Distortion patterns from global solutions

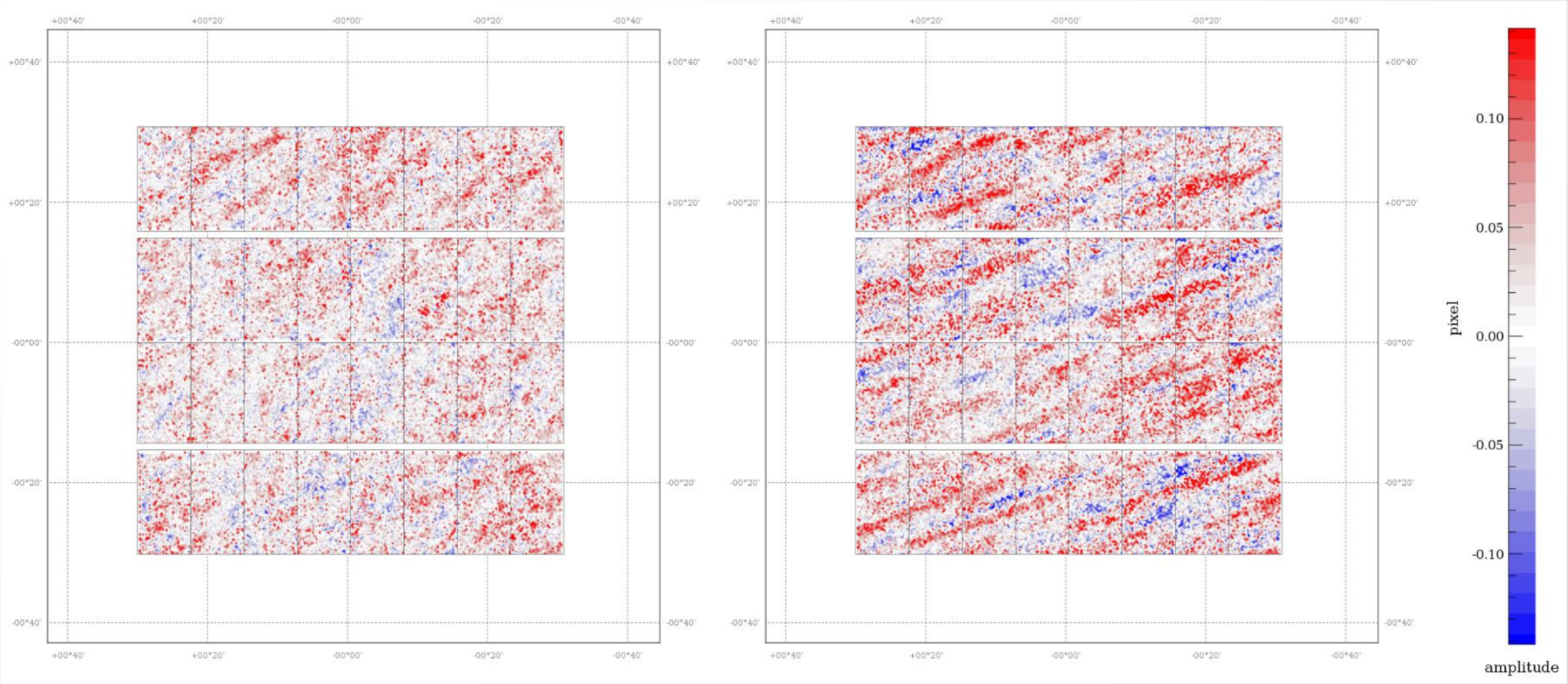


Measurement uncertainties

- Position uncertainty due to noise $\propto \frac{\mathrm{FWHM}}{\mathrm{SNR}}$
- apparent shifts due to blending with sources ≈0.1 pixel
- Turbulence:

$$\sigma(\theta, T) = \sigma_0(\theta/10')^{1/3}\,T^{-1/2} \quad \text{with } \sigma_0 \approx 54\text{mas at Mauna Kea (Han \&Gatewood 1995)}$$

$$\Rightarrow \sigma(\mathrm{FOV}, T) \approx \frac{1}{\sqrt{2}}\sigma_0\left(\frac{\mathrm{FOV}}{30'}\right)^{\frac{1}{3}} T^{-\frac{1}{2}}$$

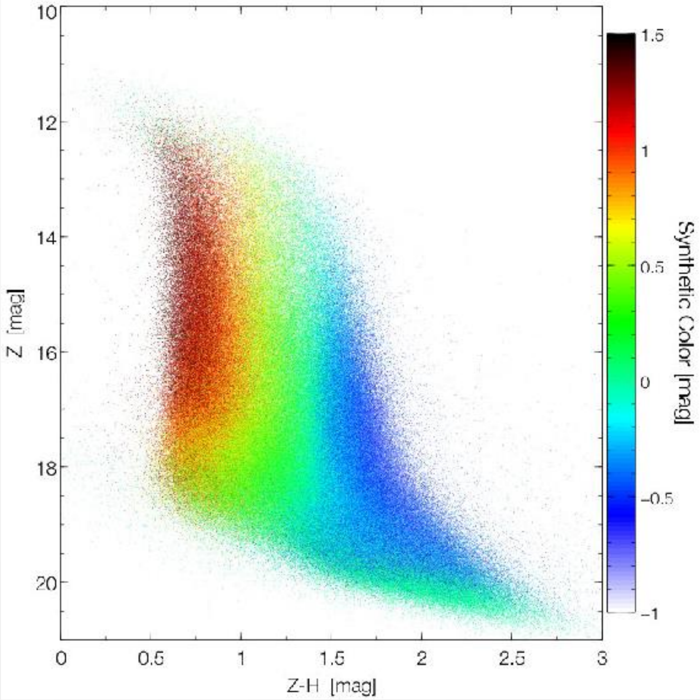


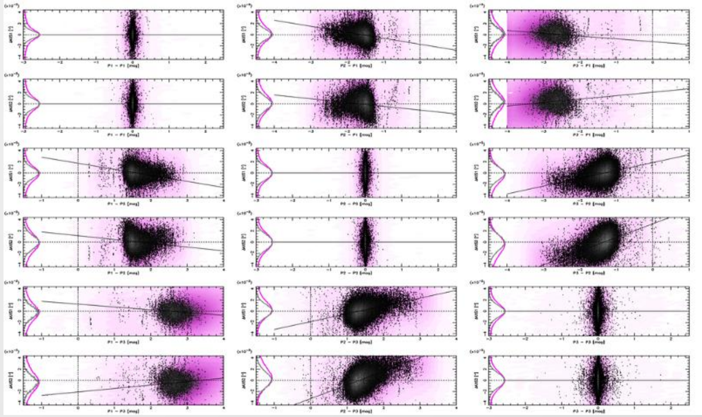
Correcting differential chromatic refraction

- 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):

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

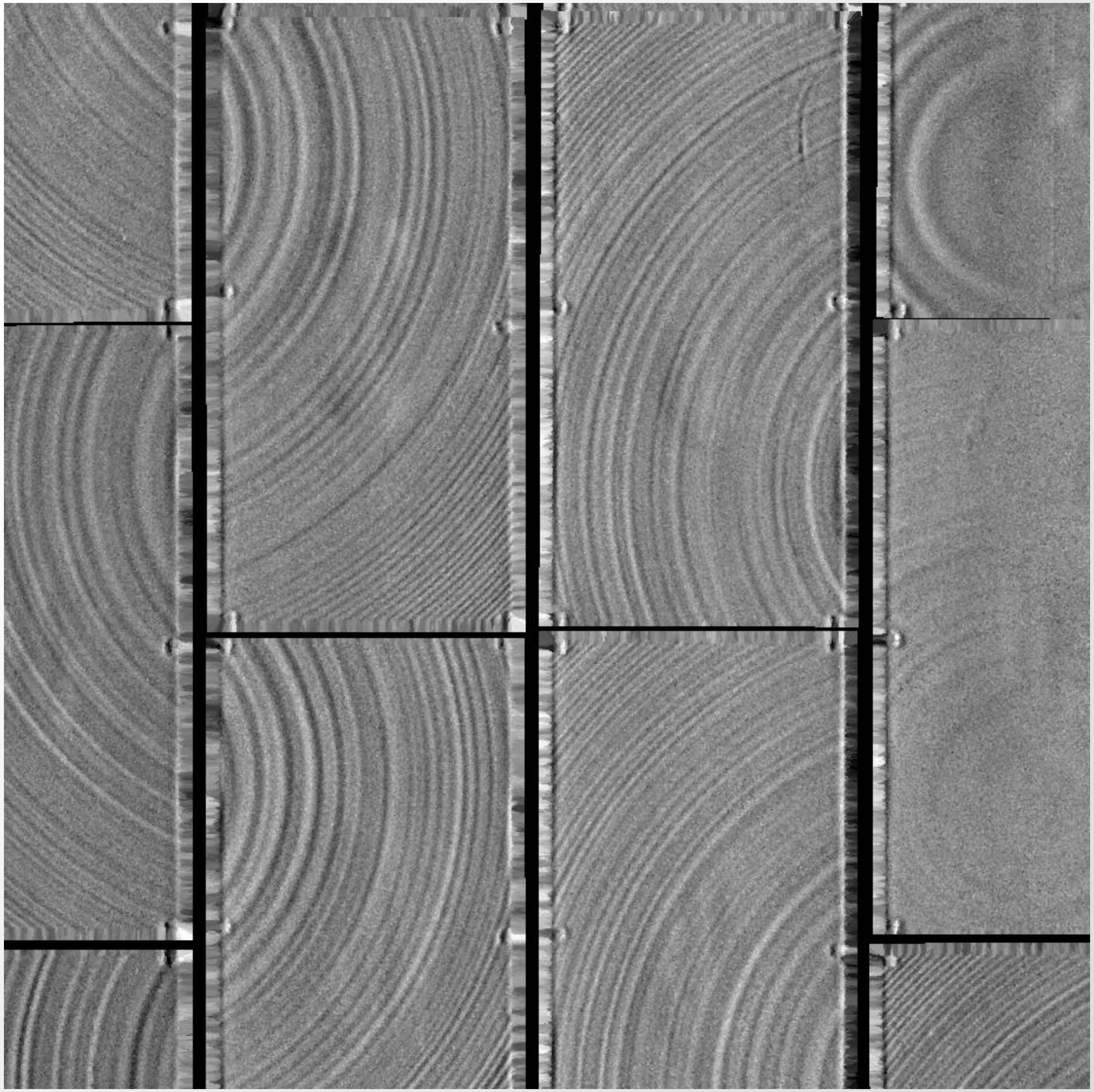
- $w \approx 0.1\,\mu$m for the u,g,r,i,z photometric system (SDSS,MEGACAM,…)
  - At z=45 deg, Δz varies from ~20mas (z band) to ~150mas (u band).
- Most ground-based catalogues are not corrected for DCR!
- We create a synthetic, global color index by assuming linear dependency between “true” color indices and correct relative position assuming that shift in position is proportional to color index.



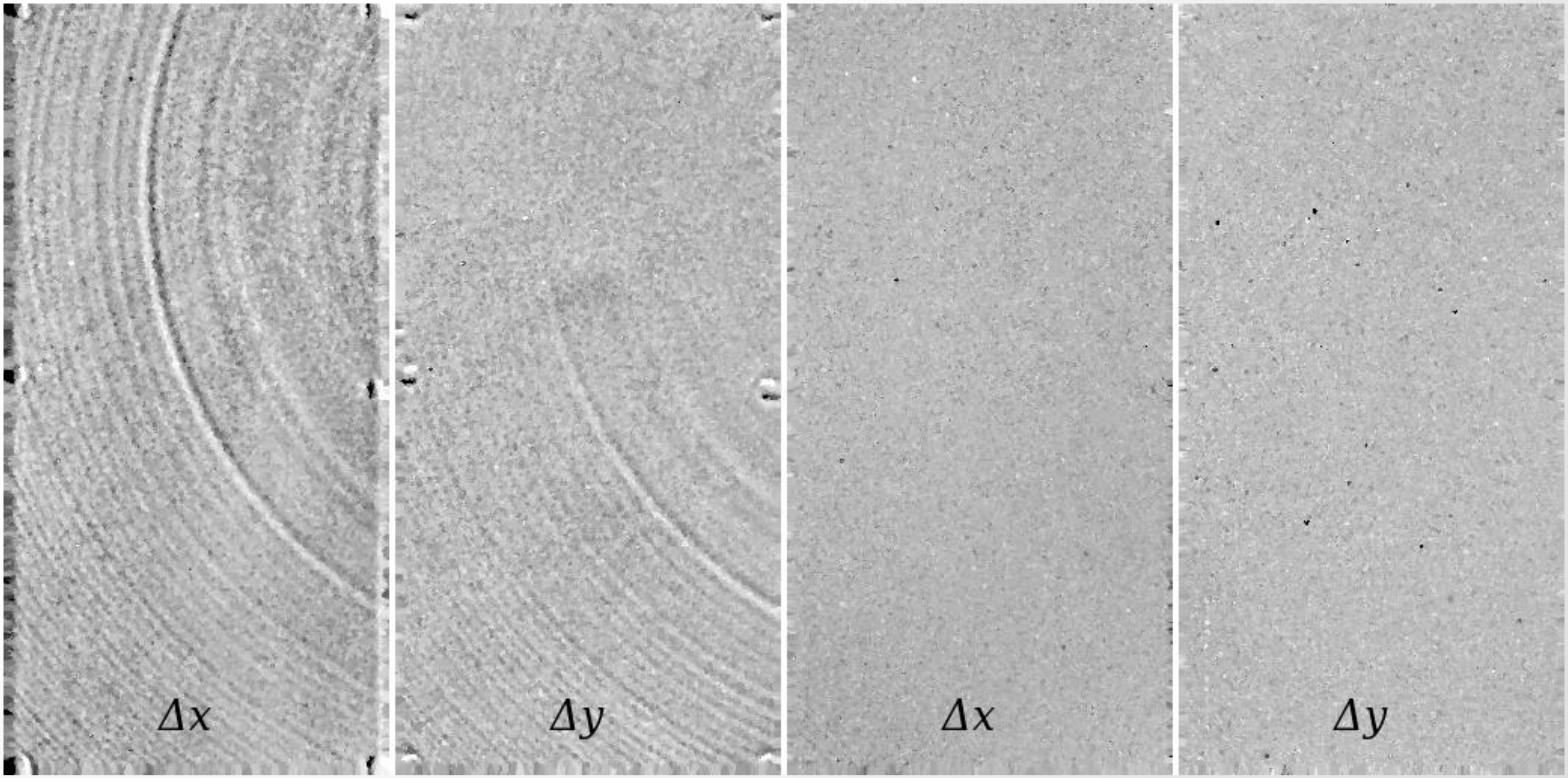


Pixel grid geometry

- Step-and-repeat periodic errors on older generations of detectors (before 2000)
- Resistivity changes (“tree rings”) on the current generation of thick depleted CCDs
  - Amplitude reaches up to 0.4 pixel peak-to-peak!
  - Differential geometry vector maps generated with SCAMP and used by SExtractor



Differential geometry correction

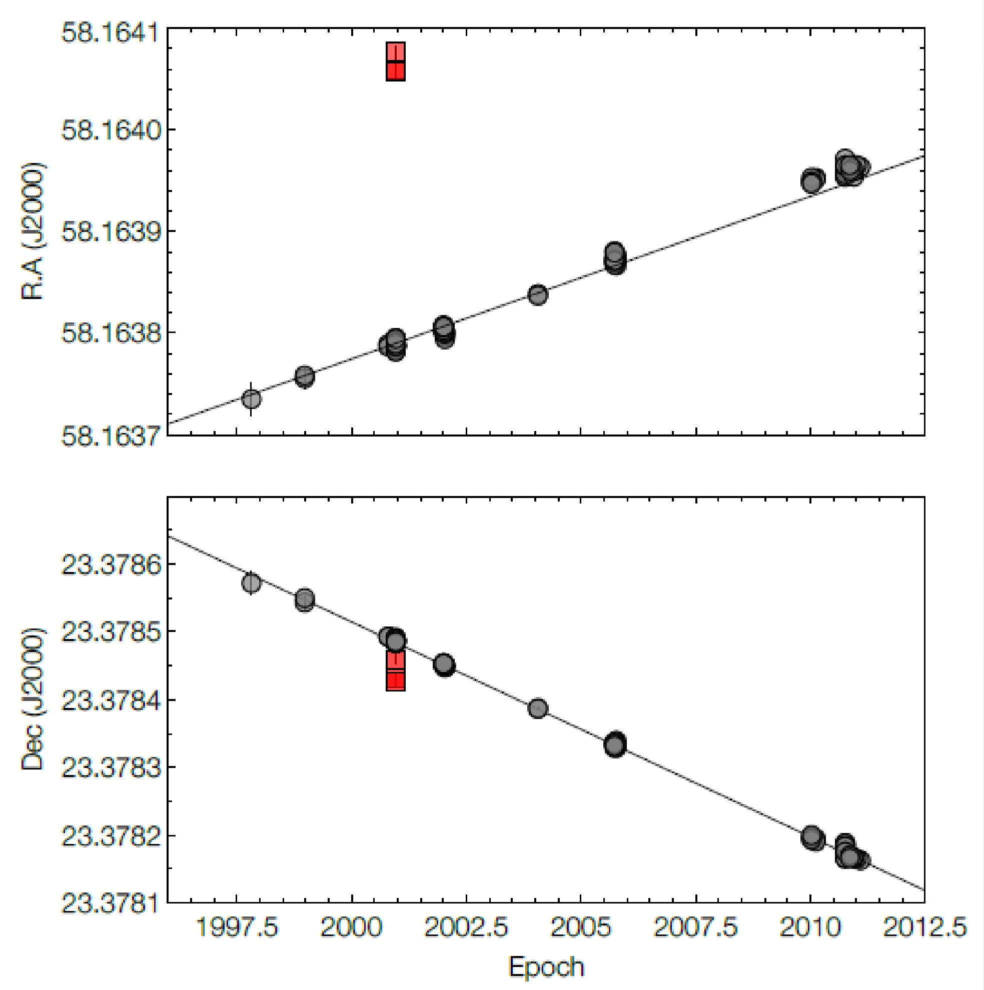


Differential geometry map derived from catalog **before** correction

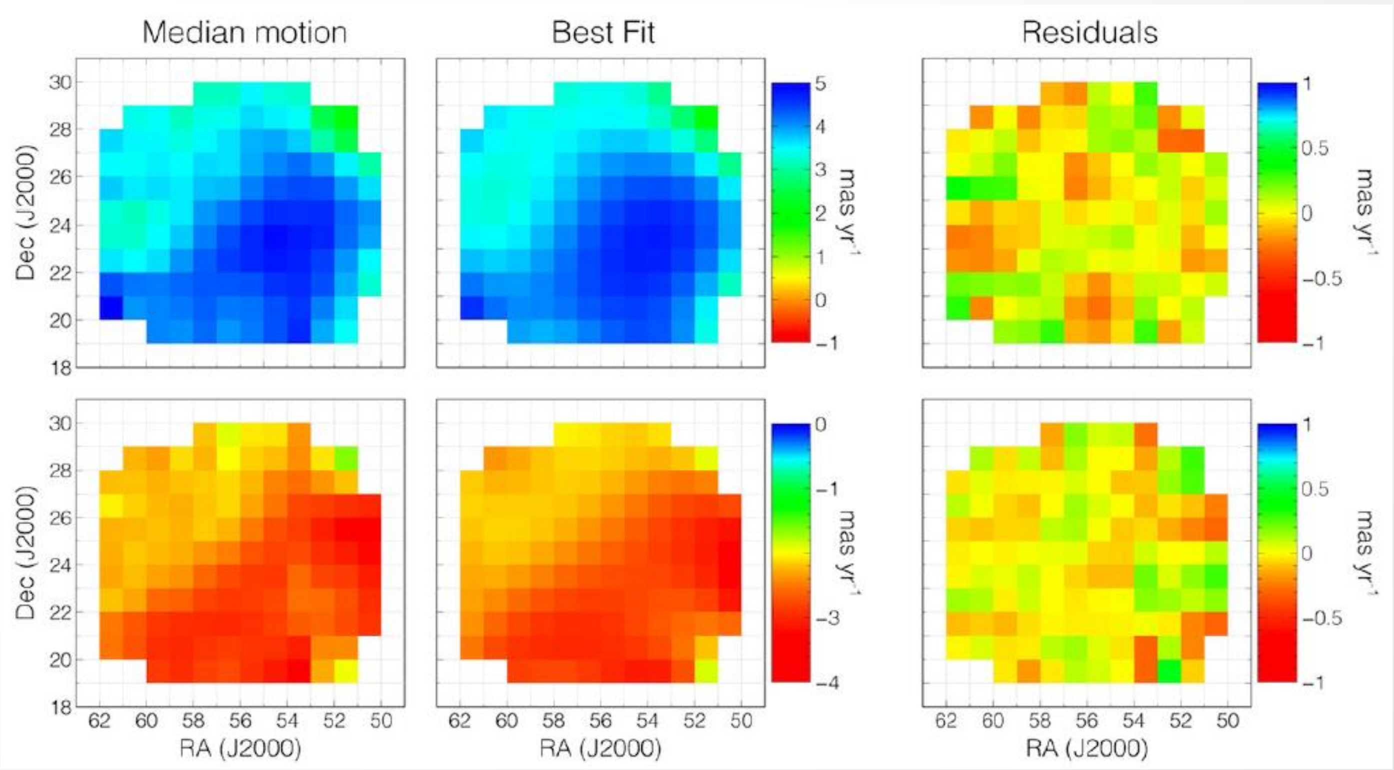
Differential geometry map derived from catalog **after** correction

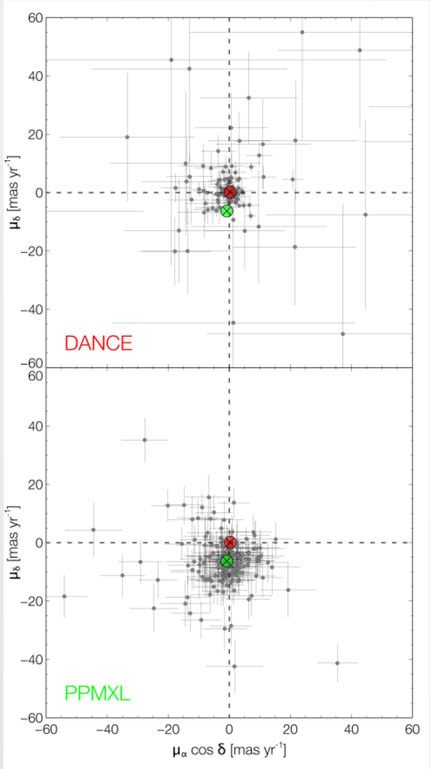
Fitting proper motions

- SCAMP can now compute proper motions from deviations to the global solution
- Iterative rejection of outliers in time sequence for each object.
- Trigonometric parallaxes were ignored



Correcting for bulk stellar motions





Proposed changes to SCAMP

- Improve iterative solver for very large problems (> 10^8 detections or > 100 astrometric contexts)
- Account for reference source proper motions
- Regularize distortion pattern solutions
- Provide calibration uncertainties
- Improve automated resolution adjustment of pattern matcher
- Improve the detection cross-matching engine
  - Performance (HealPix quad-trees)
  - Multithreading
  - Blends
  - fast moving sources
- Manage error correlations introduced by atmospheric turbulence or other effects at intermediary scales
- Manage chromatic aberrations/refraction through reduced color indices
- Allow different degrees of freedom to be used for different astrometric contexts
- Add support for SIP output and different projections for different astrometric contexts
- Implement photometric "übercal" illumination correction