Rubin Observatory

Astrometry in DM

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Princeton / Rubin Observatory DM

with lots of help

(especially John Parejko and Clare Saunders)

Outline

- What we do now
- How we're doing
- What we'd like to be doing (for transformations)
- How we'll measure Object motion parameters

What we do now (for HSC)

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- Coordinate transformation model is a composition of:
  - CCD pixels to focal plane (linear transform);
  - focal plane to tangent plane: optics + atmosphere together (7th order polynomial);
  - tangent plane to sky (gnomonic projection).
- We fit simultaneously for the transformations and the true positions of matched Sources.
- Data includes matched Source positions and reference catalog positions.
- Fit is an iteration over sparse Cholesky decompositions, using a rank update instead of a full factorization to speed up outlier rejection.
- We fit all visits in each band overlapping a tract together.

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- We fit all visits in each band overlapping a **tract** together.

Re-fitting CCD positions with every tract is unnecessary, and it *seems* to be picking up some of the atmospheric shifts, as they move around a bit from tract to tract.

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These are hard to separate because of degeneracies, but the optical distortion should be fairly stable (not per-visit), and a per-visit fit for atmosphere only could use (e.g.) a much lower order polynomial.

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- We fit all vis ct together.

We don't yet include proper motion or parallax in either the true-position model or the reference positions.

This is the "tall pole" right now.

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Works well for < 50 visits.
Slows to a crawl for 100+ visits.
Not parallel.

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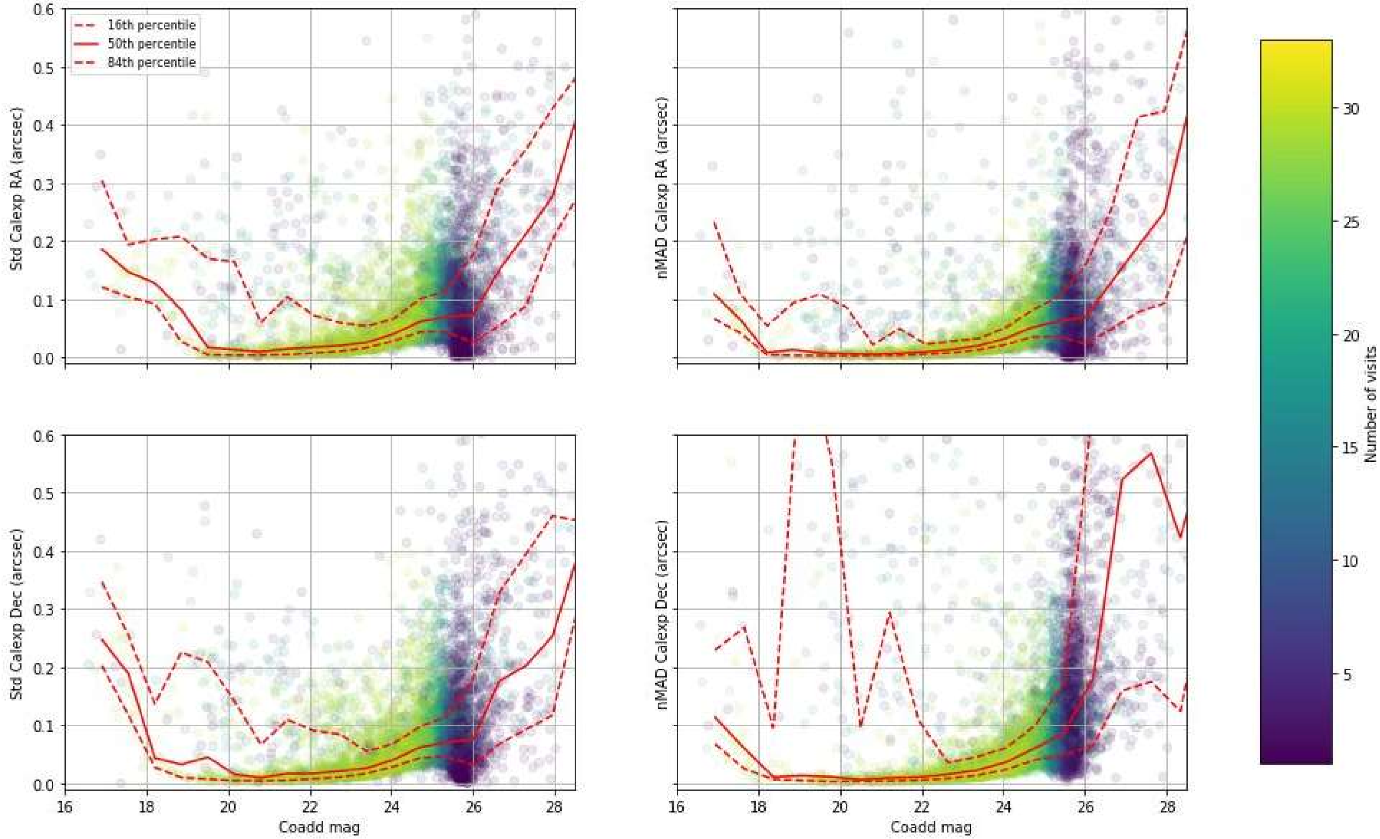
- We fit all visits **in each band** overlapping a tract together.

Fitting each band independently means that we can't yet include chromatic effects.

How we're doing

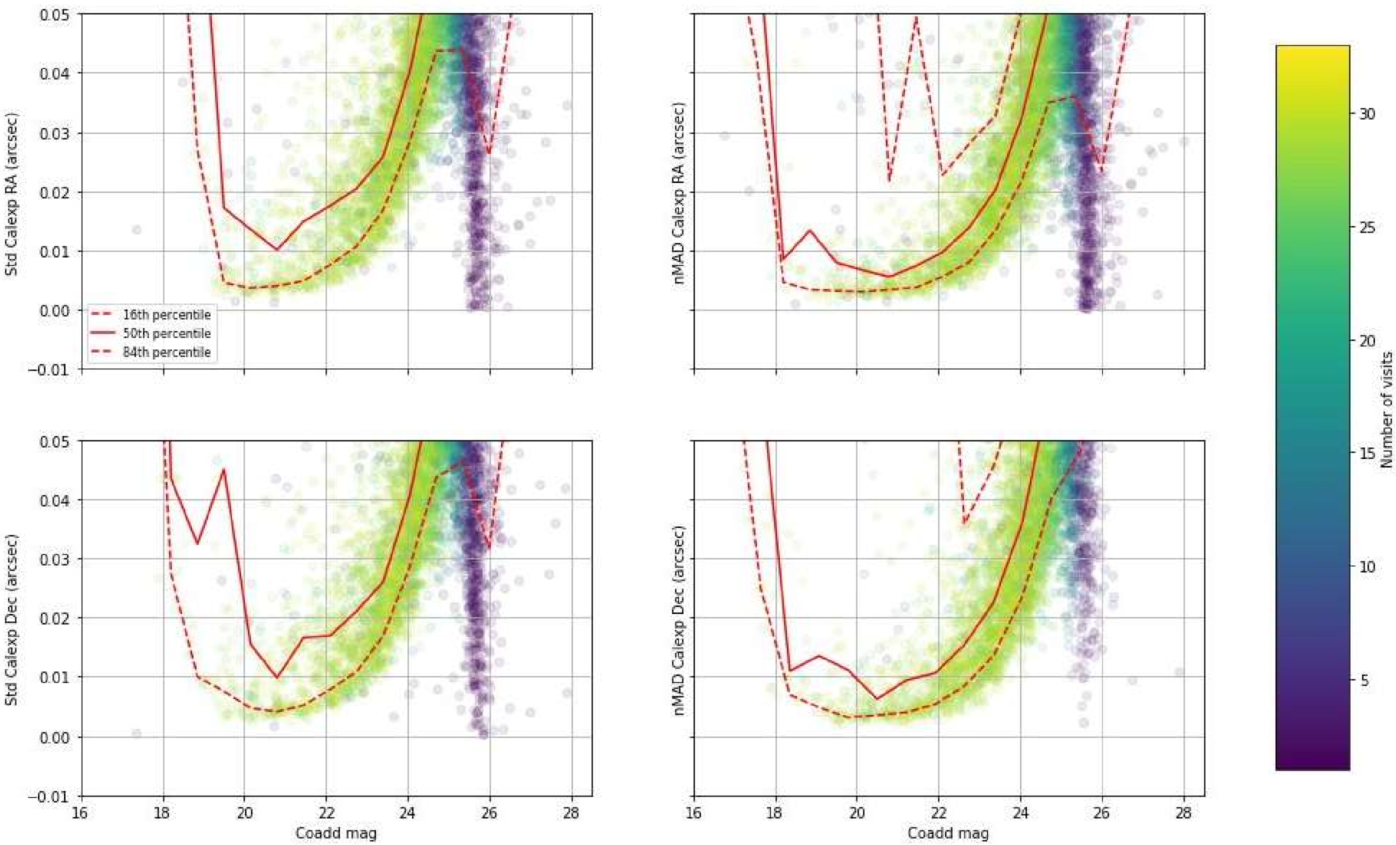
Matched source repeatability



- Centroids measured on calexp (single-visit) images;
- Transformed via joint-fitting WCSs.
- Matched via coadd Object list (where magnitudes are from).

Slide from Clare Saunders

Matched source repeatability



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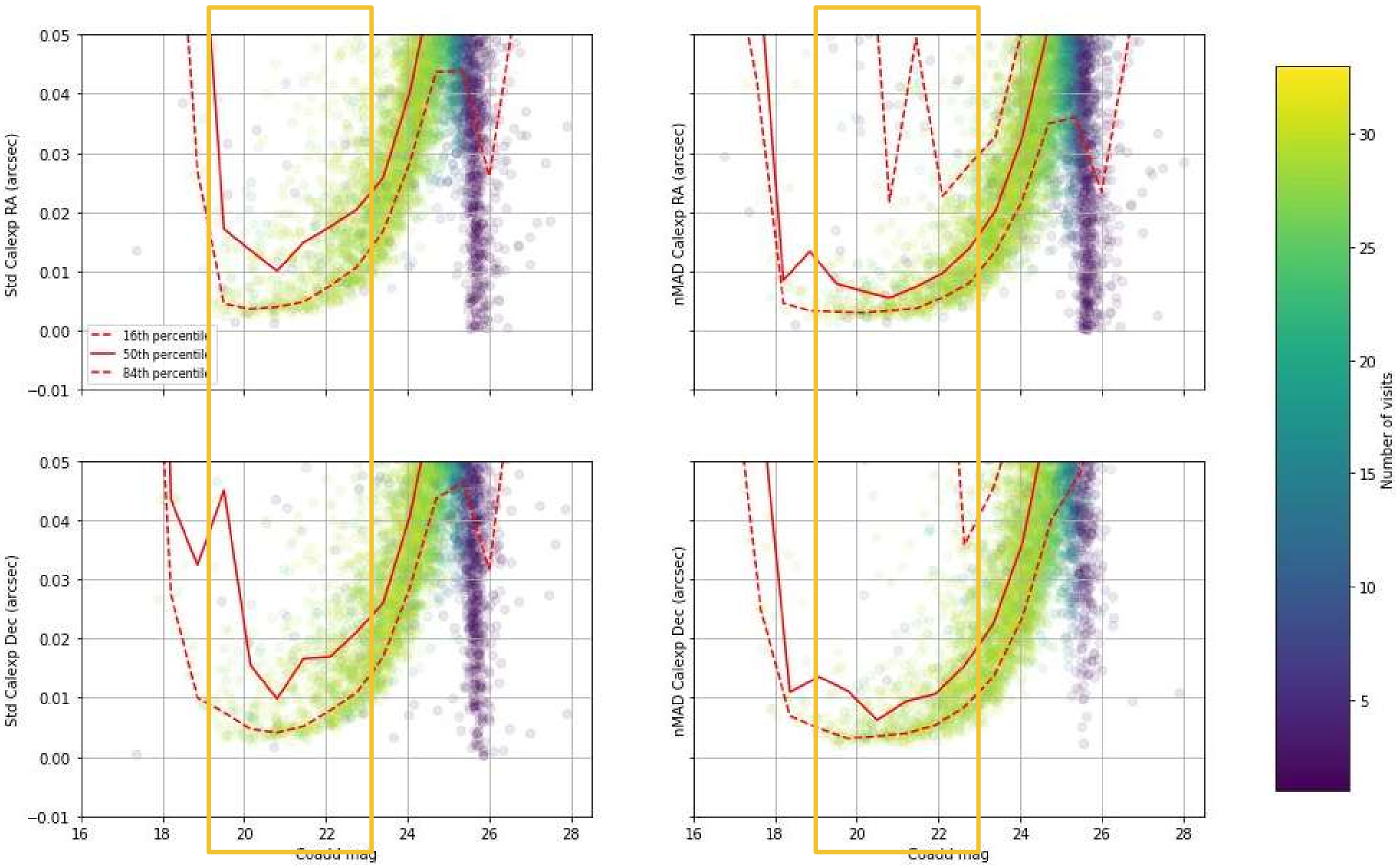

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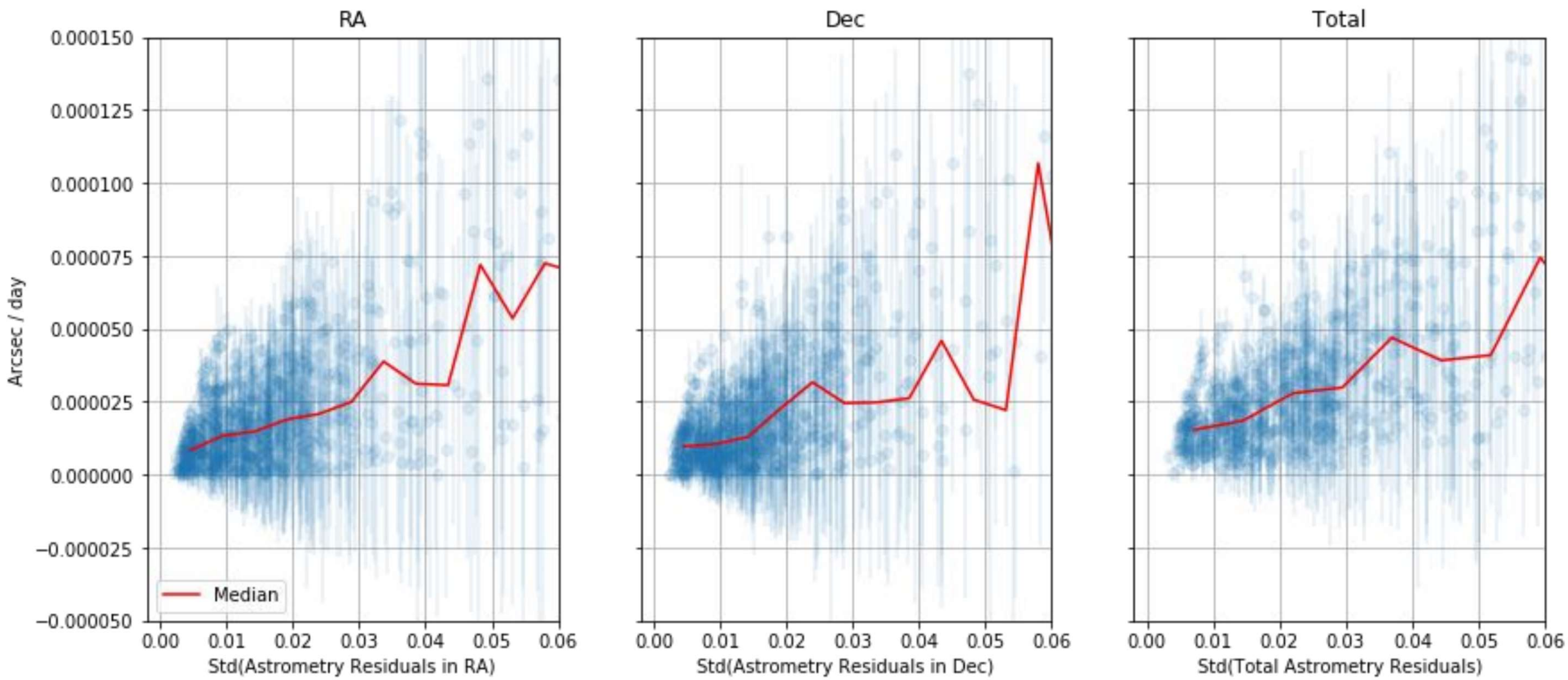
Peculiar velocities



Slide from Clare Saunders

LSST Science Requirements Document metrics

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Our highest-level SRD requirements are actually on the repeatability of distances between *pairs* of bright, isolated stars on ~CCD (5'), raft (20'), and focal-plane scales (200') scales.

This definition is intended to average out stochastic effects (photon noise, atmospheric turbulence), so the numbers will be smaller than the traditional per-object repeatability of the last few plots.

I'm not completely confident that applying these metrics to HSC data (different pixel sizes, much better seeing, much longer exposures, many fewer epochs) will predict how they will behave for LSST, but they're the best we have right now.

Pairwise repeatability at 5'

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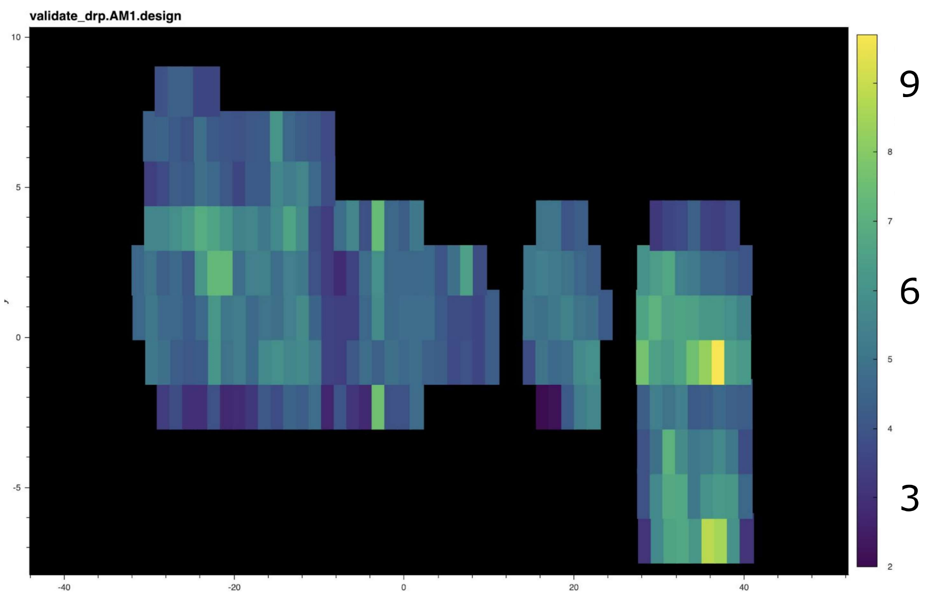
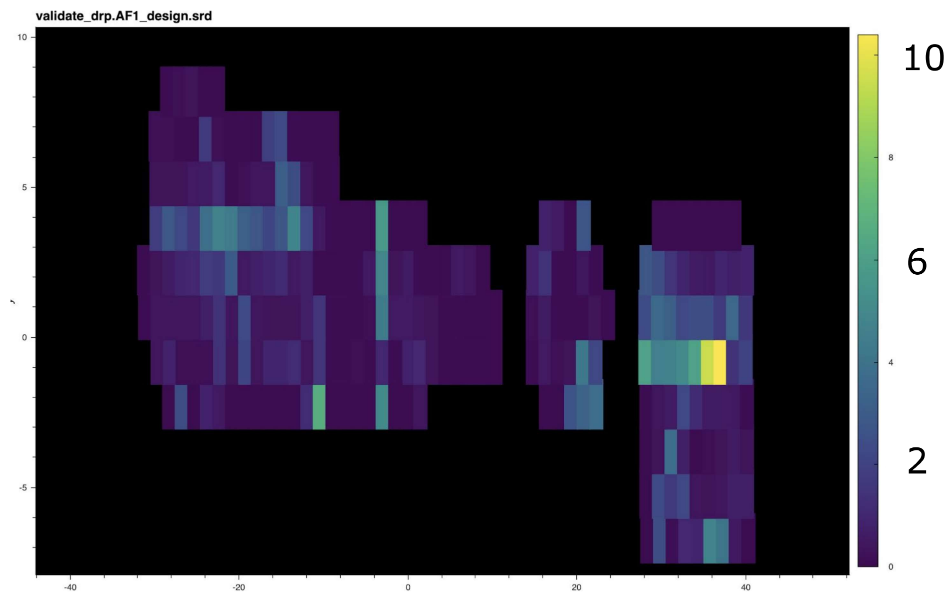
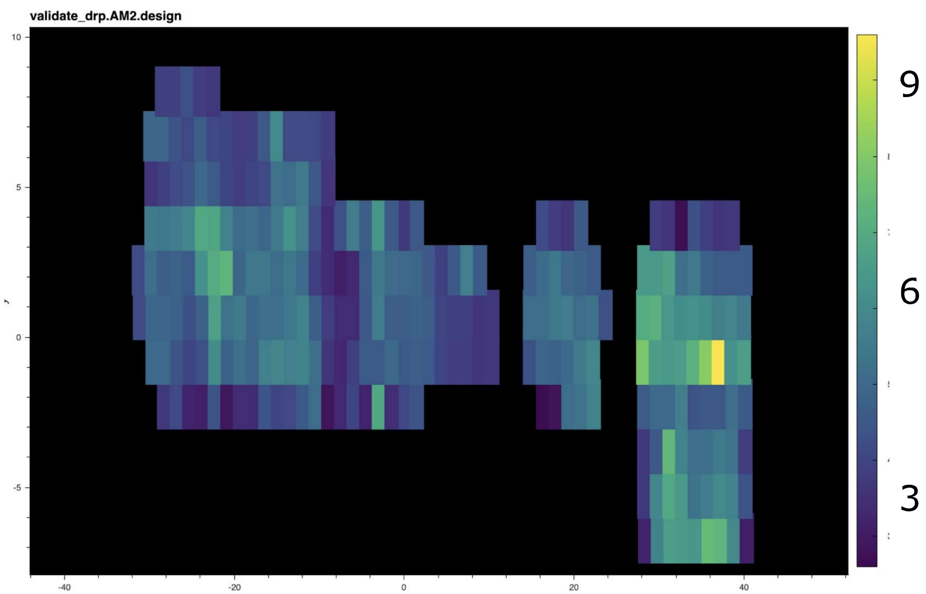


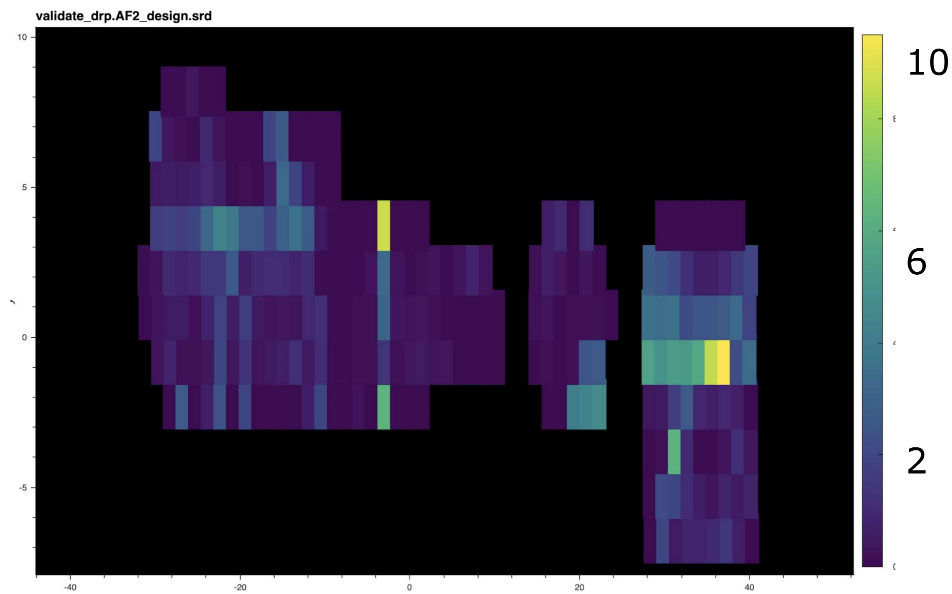


RMS repeatability (mas)
minimum/design/stretch: 20/10/5

Fraction more than 20mas from median
minimum/design/stretch: 20/10/5

Pairwise repeatability at 20'





RMS repeatability (mas)
minimum/design/stretch: 20/10/5

Fraction more than 20mas from median
minimum/design/stretch: 20/10/5

What we'd like to be doing (for transformations)

Avoiding per-Source offset systematics

1. Switch to Gaia as the reference catalog.
2. Include reference-catalog proper motion and parallax.
3. Include proper motion and parallax parameters in the fitting.
4. Predict DCR offsets from broad-band colors.

Instrument calibration fitting

In some special (or maybe random) patch of sky, fit a more sophisticated model:

- true CCD pixels to ideal CCD pixels (temporally constant);
- ideal CCD pixels to focal plane (temporally constant);
- focal plane to tangent plane, without atmosphere (may depend weakly on physical degrees of freedom in the optics, wavelength);
- atmospheric distortions (nuisance parameters at this point).

We'd hold these transformations fixed while fitting atmospheric distortions and constraining physical degrees of freedom to each visit or tract.

Getting to what we'd like to be doing

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Gary Bernstein just talked about what he's done with astrometric calibration for DECam.

It is not a coincidence that what we'd like to do sounds a lot like what he has done.

His code has a substantial lead on ours in terms of functionality, and his approach to the linear algebra gives us some hope that it may scale better.

We've been evaluating switching to using his code, but integration would not be easy.

Measuring Object motions

The original plan: multifit

After fitting transformations, we had planned to:

1. Build, detect, deblend, and measure "static sky" Objects on coadds.
2. For each Object, load its pixels in all single-visit images, and fit a 6-parameter (2× position, 2× proper motion, parallax flux) model to all of them together.

This is similar to Lang et al 2009 (on SDSS Stripe 82). But:

- We never had a coherent story for how to handle blending here.
- This is an inefficient use of compute resources, and something we'd prefer not to have to devote developer resources to either.

One probable piece: matched Source motions

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Astrometric measurements have historically been done by catalog-space fits to per-epoch centroids. But, for LSST:

- Some Objects will not have multi-Source matches (Objects go deeper).
- Some multi-Source matches will not associate cleanly with Objects (due to blending).

We hope to use these fits as a starting point for better modeling. Just reporting them (only for objects with clear associations) is our worst-case scenario.

Another (eventual) piece: short-period coadds

We'll eventually be making yearly coadds, aimed at detecting high-proper-motion stars.

We can simultaneously fit proper motions to the suite of yearly coadds as well.

- It probably makes sense to do all of this on differences between early coadds rather than the coadds themselves.
- This enables measurement of proper motion (but not parallax) on stars below the single-visit detection limit.

A final (theoretical) piece: forced difference dipoles

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Image subtraction is reversible: you can reconstruct the original image from the difference and the template.

That means the template plus the differences (together) are a sufficient statistic for the original images, and everything we could have learned from multifit should be doable on coadds and difference images instead, and

- we *do* know how to handle blends on the coadd*;
- blends will be much rarer in the difference images.

A final (theoretical) piece: forced difference dipoles

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If we can predict the per-epoch positions of all Objects well enough (from matched-Source fitting and/or yearly coadds), we can:

- measure a "forced dipole moment" with those positions, on the difference images (on image at a time, instead of one Object at a time)
- fit the final motion model in catalog-space.

The loss in S/N relative to multifit should just be a not-quite-optimal weight function for the forced dipoles (because we're using the predicted rather than best-fit position). This should be tiny if the offset is small relative to the PSF.

Where this leaves us

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- Our coordinate transformation fitting is behind the state of the art, but it is good enough not to be a limiting factor for *many* LSST science goals.
- It is definitely not good enough for some very important LSST science goals.
- We have essentially *nothing* in terms of stellar motion fitting so far.

Where this leaves us

- I think we have a credible scheme for getting to the state of the art (matched-Source motion fits).
- I think we have a plausible scheme for pushing beyond that, and measuring motions for all Objects (even those below the single-epoch detection limit).
- Most of this work is not even started - I am worried, and you should be too.

Extra slides

Before and after joint fitting: SRD metrics

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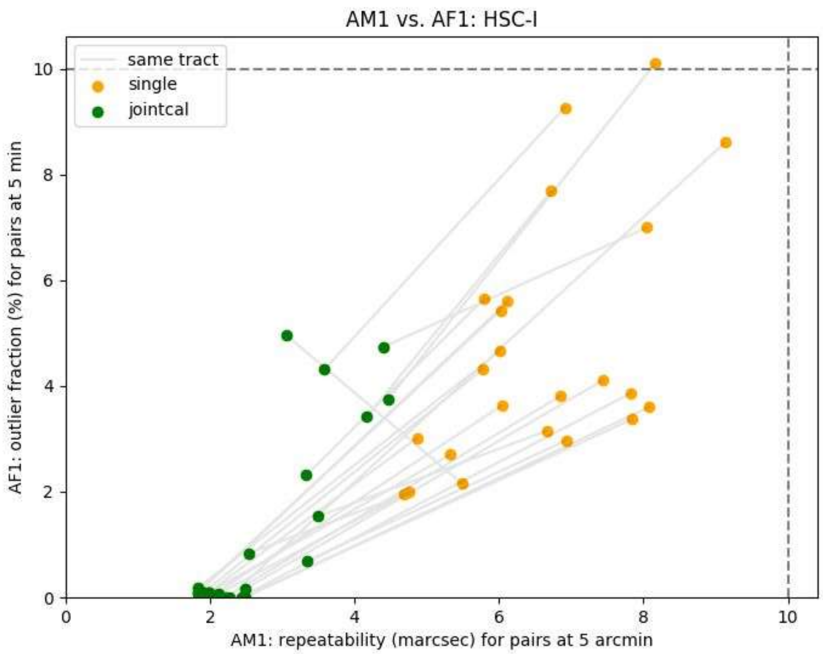
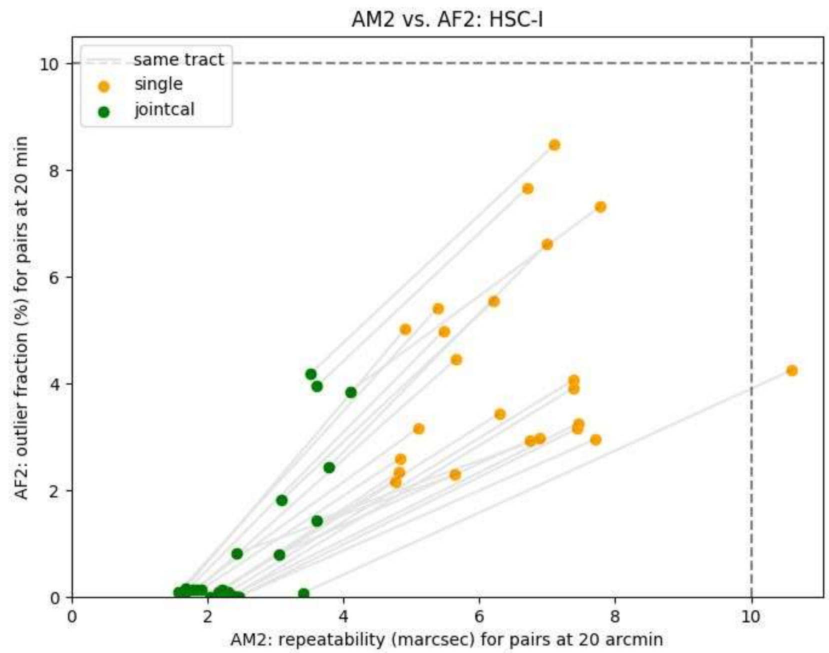
Using joint fitting is much better than just using single-epoch fitting to a reference catalog (but even the latter mostly meets requirements?!)

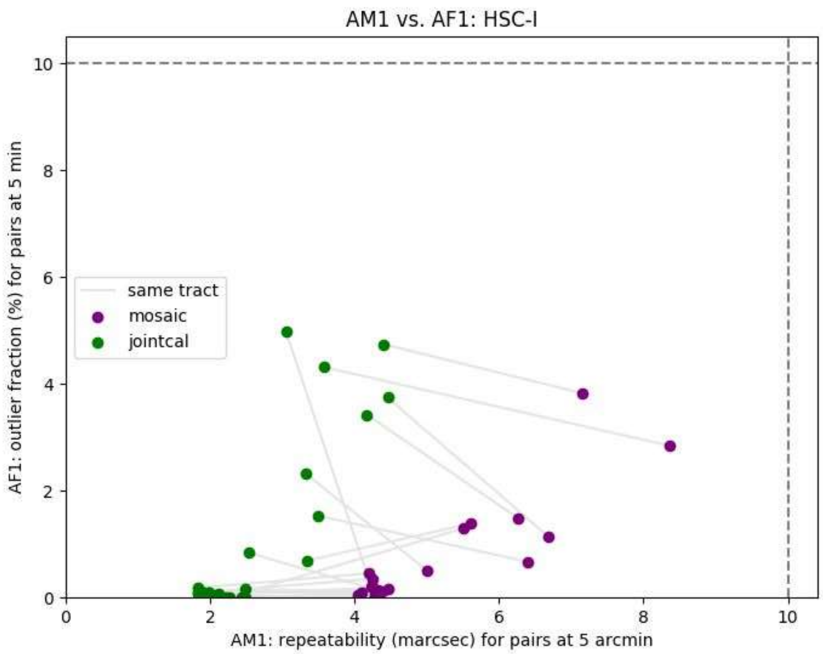


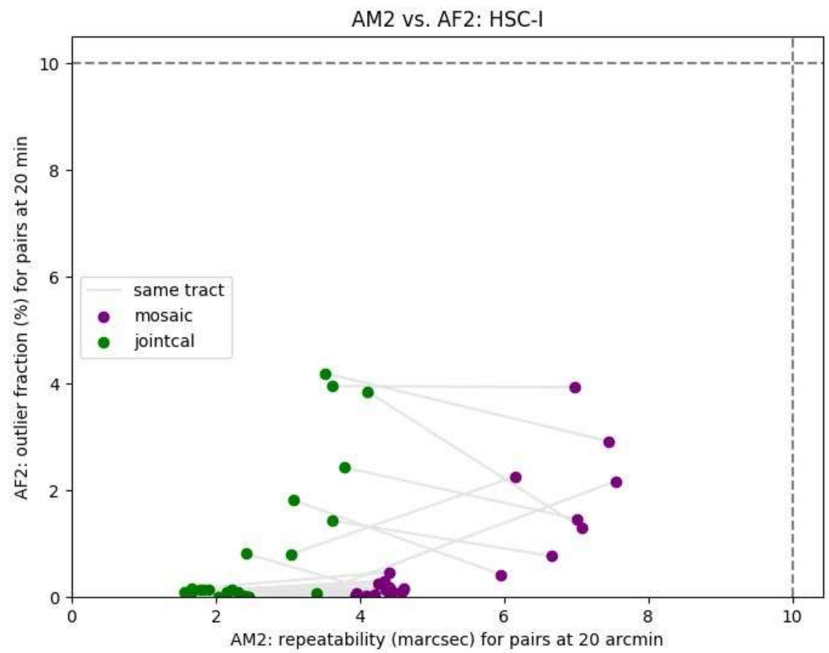


Figures from John Parejko

Relative to our previous fitter (meas_mosaic)

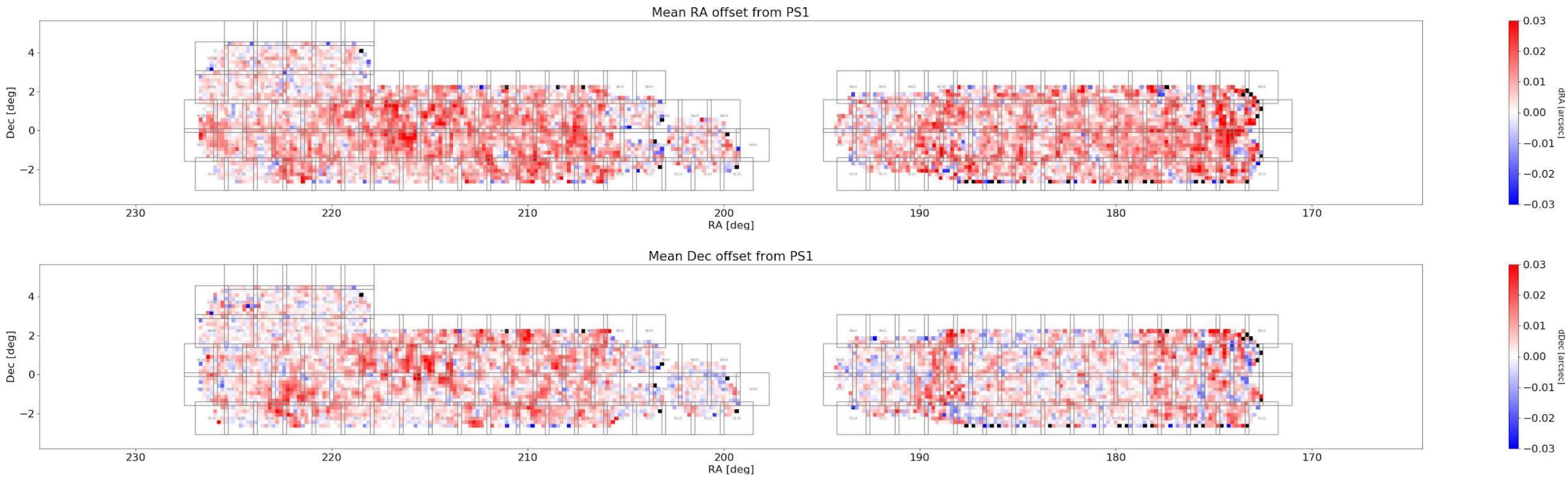
These fit similar models, with slightly different outlier rejection and optimization algorithms.





Figures from John Parejko

Offsets from PS1



These plots were made with fits from meas_mosaic; the processing for jointcal versions didn't finish in time.

Figures from NAOJ ([HSC PDR2](HSC PDR2))

Offsets from Gaia

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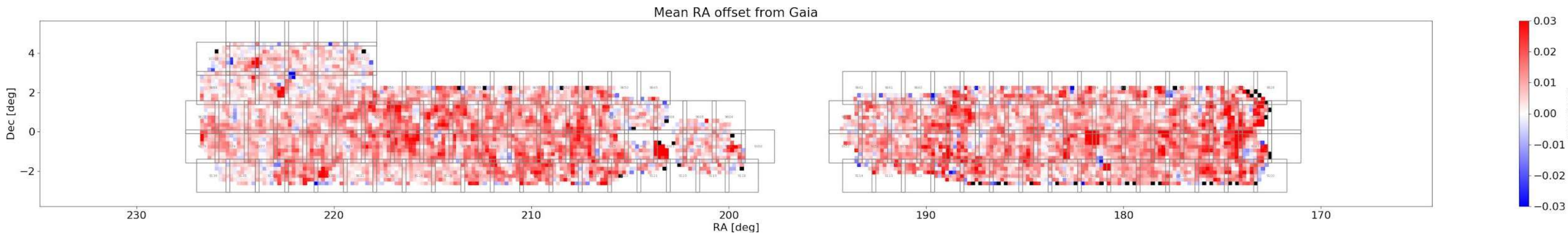

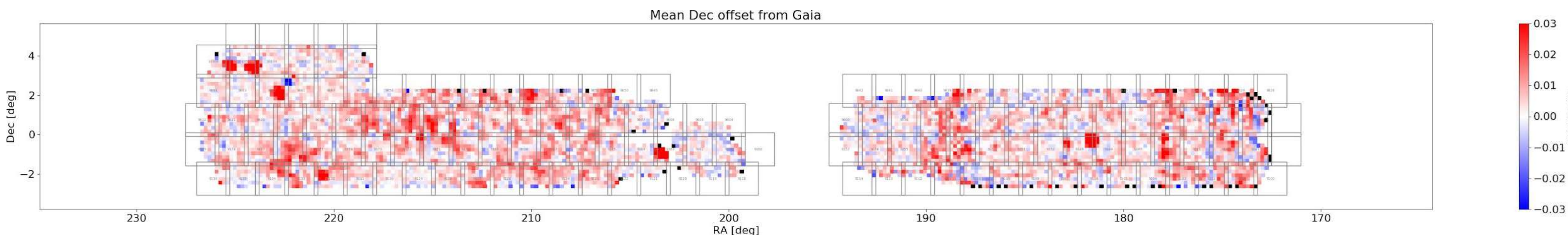

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