PSF modeling plans
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Existing DM PSF framework

- Most widely used algorithm is PSFex
- Limited to running 1 sensor at a time
- We know we’ll need to iterate for chromatic effects:
  - Initial PSF -> photometry -> better chromatic PSF
- Intend to include differential chromatic refraction as part of PSF (as opposed to WCS, where only DCR 1st moment could ever be included).
The goal for the future: a modular PSF

- PSF = Convolve(atmosphere, optics, CCD)

- Advantages:
  
  - **Robust**: small number of variables to describe full-field optics variations
  
  - Capture **chip discontinuities** in static optics PSF, allowing atmospheric PSF to be interpolated across entire focal plane
  
  - Easier modeling of PSF **chromaticity**, we have good models for how individual components behave chromatically.
A challenge: discontinuities

- Current PSF packages: fit individual stars using parametric model, interpolate coefficients
- CCD gaps $\Rightarrow$ discontinuities
  - Limits packages to working one CCD at a time.
- Uniform distribution of heights between +/- 5 microns leads to size discontinuities of $\sim 1\%$ after convolution with atmosphere, sensor PSF contributions.
A challenge: discontinuities

- Current PSF packages: fit individual stars using parametric model, interpolate coefficients
- CCD gaps => discontinuities
  - Limits packages to working one CCD at a time.
- Uniform distribution of heights between +/- 5 microns leads to size discontinuities of ~1% after convolution with atmosphere, sensor PSF contributions.
An opportunity: long range correlations

- Atmospheric PSF often contains interesting **anisotropic spatial correlations**.
- Most interpolation algorithms can’t take advantage of this.
- Proposal is to use a **Gaussian process** with anisotropic kernel to model this.
- Initially interpolate parameters of Von Karman surface brightness profile, but other parameterizations also possible.

```
  e1  CFHT data  e2

Heymans++12
```

Credit: PF Leget
Modeling Strategy

- PSF = convolve(optics, atm, ccd)
  - optics = static + dynamic
  - Forward model: fit via chi-square minimization or related.

- Preprocessing: using many donut exposures, fit for static and dynamic optics terms.
  - (Atmosphere is relatively less important for donuts)

- Holding static optics terms fixed, fit an in-focus exposure iteratively:
  - First iteration: degrees of freedom are dynamic optics + uniform atm.
  - Second iteration: hold optics terms fixed and fit individual star atm components.
  - Interpolate atm components (GP?)
  - Repeat as desired.
Optics model - Fourier optics

\[ I(\vec{\theta}; \vec{x}) \propto \mathcal{F} \left[ P(\vec{\theta}; \vec{u}) \exp \left( \frac{-2\pi i}{\lambda} W(\vec{\theta}; \vec{u}) \right) \right]^2 \]

- \( \vec{\theta} \) = sky
- \( \vec{x} \) = image
- \( \vec{u} \) = pupil

pupil illumination

wavefront
Wavefront model

\[ W^i(u; \theta) = W_{\text{tel}}(u; \theta) + W_{\text{CCD}}(R^i u; R^i \theta) + W_{\text{visit}}(u; \theta) \]

"reference" wavefront

- Wavefront is the sum of contributions from:
  - **Telescope**
    - static; continuous; may vary quickly over focal plane due to figure errors
  - **CCD height variations**
    - static; contains discontinuities; needs to de-rotate wrt telescope
  - **Per-visit aberrations**
    - dynamic; continuous; slow variation over focal plane; kinds of variations are predictable
Express wavefront as double Zernike series

For one star, pupil wavefront is Zernike series

\[ W^* (\vec{u}) = \sum_{j=4} a_j^* Z_j (\vec{u}) \]

For entire field of view, let coefficient also be Zernike series

\[ a_j (\vec{\theta}) = \sum_{k=1} a_{jk} Z_j (\vec{\theta}) \]

Double Zernike series

\[ W (\vec{u}, \vec{\theta}) = \sum_{j=4} \sum_{k=1} a_{jk} Z_j (\vec{u}) Z_k (\vec{\theta}) \]
Misalignments, bending modes introduce low-order patterns

- Dynamic part of optics (flexure) is modelable using only a few low-order double Zernike terms.

- Rigid body of Camera + M2:
  - \( \sim 9 \) DZ terms

- Rigid body + 10 M1M3 modes:
  - \( \sim 17 \) DZ terms

- Rigid body + 20 M1M3 modes:
  - \( \sim 34 \) DZ terms
Building the reference wavefront

- Use metrology obtained during construction, or measure directly from donuts.

- DECam reference wavefront obtained by low-order detrending to remove flexure followed by taking mean of all donut exposure Zernike coefficients.

- Rubin Obs reference wavefront requires two pieces b/c of presence of rotator.

- Can solve a large linear algebra problem to obtain.
Separating wavefront components

- We can take series of donut measurements at different rotator angles to tease apart different contributions to reference wavefront.

\[
\sum_{j=1}^{j_{\text{max}}} a_j^i(\tilde{\theta}_*) Z_j(\tilde{\nu}) = \sum_{jk} b_{jk}^{\text{tel}} Z_k(\tilde{\theta}_*) Z_j(\tilde{\nu}) + \sum_{jk} c_{jk}^i Z_k(\tilde{\theta}_*) Z_j(\tilde{\nu})
\]

- (Don’t need to grok this slide now, just here for reference and to show general idea...)

- Can solve this for the b’s and c’s term-by-term (indep for each j)

\[
a_j^i(\tilde{\theta}_*) = \sum_{k} b_{jk}^{\text{tel}} Z_k(\tilde{\theta}_*) + \sum_{k} c_{jk}^i Z_k(\tilde{\theta}_*)
\]

- Matrix equation roughly:

\[
\begin{pmatrix}
Z_k(\tilde{\theta}_*)'s \\
\end{pmatrix}
\begin{pmatrix}
b's \\
c's
\end{pmatrix}
= \begin{pmatrix}
a's
\end{pmatrix}
\]

Also require

\[
\sum_{i} c_{jk}^i = 0
\]
HSC design matrix example

- Color of filled in cells determined by rotator angle and position of * in focal plane.
- All stars contribute to our knowledge of telescope.
- Each star contributes to one CCD term and one per-visit term.
- Visit solutions only good for particular training exposures, but CCD and telescope terms are useful for all Rubin obs exposures.
- Repeat for each pupil Zernike coefficient (or pair of related coefficients).
$W_{\text{tel}}$ results for HSC

Location is FoV
Color is pupil term amplitude
$W_{\text{CCD}}$ results for HSC

Location is FoV
Color is pupil term amplitude
$W_{\text{visit}}$ results for a few HSC exposures

Location is FoV
Color is pupil term amplitude
W_{\text{visit}} results for a few HSC exposures

Location is FoV
Color is pupil term amplitude
$W_{\text{visit}}$ results for a few HSC exposures

Location is FoV
Color is pupil term amplitude
$W_{\text{visit}}$ results for a few HSC exposures

$W_{\text{visit}}$ visit 69034

Location is FoV
Color is pupil term amplitude
Results for HSC

- Visit E9016
- Location is FoV
- Color is pupil term amplitude
Results for HSC

Location is FoV
Color is pupil term amplitude
Results for HSC

Location is FoV
Color is pupil term amplitude
Results for HSC

- Fitting to new **in-focus** exposures is accomplished by fixing the static degrees of freedom inferred from donuts, but allowing the dynamic degrees of freedom to vary.

- Can even learn per-visit degrees of freedom from principle components of donut exposures.

- This is model on right: simple uniform-across FoV model for Atm PSF here...

- Generally reasonable output, but HSC limited by small number of donut exposures.

- For Rubin Obs, should also investigate using WF sensors to infer dynamical state.
Results for DECam

- Dynamic degrees of freedom are a handful of low-order Zernikes here.
- Atm PSF is uniform-across-FoV vonKarman surface brightness profile.
- Capture most of the PSF using ~dozen numbers.

Figure credit: Ares Hernandez
Interpolate atmospheric component with Gaussian Process

- After optics PSF inference:
  - Refit PSF stars, holding optics fixed, allowing atm params to vary independently for each star.
  - Interpolate parameters of atm component using Gaussian Process.

- Gaussian process:
  - Models directly the (potentially anisotropic) correlations in a function instead of the function itself.
  - Pierre-Francois Leget has made significant progress in rapidly modeling correlations.

- With correlation model in hand, can interpolate from data.
  - Every prediction is a linear combination of data, with relative weights set by model correlation of prediction point with data point (set by displacement between prediction and data point)
  - Many approximate GPs exist with speedier maths.
Piff

- Mike showed earlier that Piff is already superior to PSFex for DES
- Framework for modular PSF is now being developed in Piff
- We are planning to integrate Piff into the DM stack.
- Two tasks:
  - 1) Ability to run Piff on Rubin Obs images (already demonstrated by Mike with DC2 images)
  - 2) Ability to use Piff PSF outputs in subsequent stack measurement algorithms.
Chromatic effects

- PSF = PSF(\lambda)
- There are many:
  - Differential chromatic refraction
  - Chromatic seeing
  - Dispersive optics
  - Diffraction
  - Absorption length of silicon coupled with:
    - fast beam
    - charge diffusion
    - lateral electric fields
  - Reflections off backside of silicon.

Josh’s favorite chromatic effect: silicon absorption length + fast beam

In blue, all photons convert at surface

In red, redder photons convert deeper, and b/c converging beam, over different range laterally.
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Modeling chromatic effects

• Keep in mind that stars are “easy.” Their SEDs are essentially a one-parameter family (temperature).

• We have good models for many individual components of PSF(\(\lambda\)) (optics/atm/ccd/etc).

• I have confidence we can infer PSF(\(\lambda\)).
  • Fallback option: Pfiff PixelGrid regressed on color. (2x params; enough stars?)
  • Hard part is inferring galactic SEDs from photometry to construct PSF to use in galaxy measurements.
  • This is similar to photo-zs, except no catastrophic outliers.

• The zero-order solution is to model SEDs linearly across bands using neighboring bands’ colors.

• There’s an interesting question for meta-detection, part of which uses a single PSF by which to deconvolve a small scene of objects with potentially disparate SEDs.
Conclusions

• Let’s adopt Piff!
  • Better than PSFex
  • Has room for baseline chromatic PSF

• Making progress with wavefront model, but still work to be done.