Focal Plane Fitting With Templates

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The Simons Observatory

Next generation CMB observatory consisting of one 6 meter Large Aperture Telescope (LAT) and three 42 cm Small Aperture Telescopes (SATs) with more SATs coming from SO:UK and SO:Japan.

Figure 1: The LAT

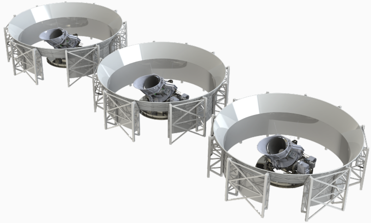


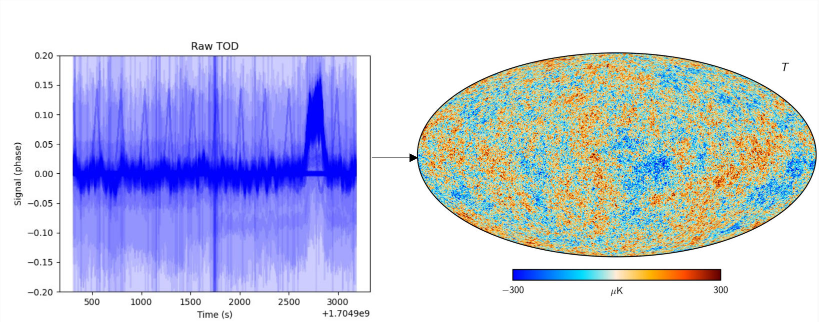
Figure 2: The SATs

TOD → Maps

For much of the science we want to extract from these telescopes we want to first solve:

$$d = Pm + n$$

to go from time ordered data (TODs) to maps.



The SO Pipeline

Many steps before we even get to mapmaking:

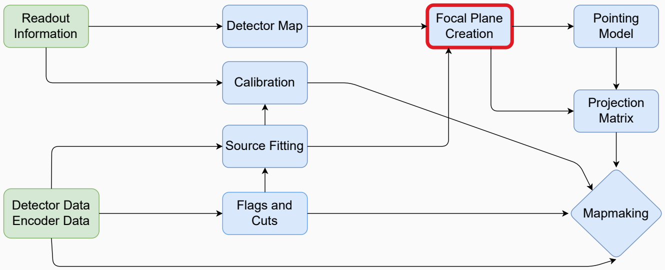


Figure 4: Partial flowchart of SO pipeline

but lets focus on the stuff that goes into making P.

Most of this code is in simonsobs/sotodlib

Fitting Detector Offsets

Hybrid map plus TOD based procedure:

- Make single detector maps to get a rough idea positions
- Use these positions as priors to fit in the time domain

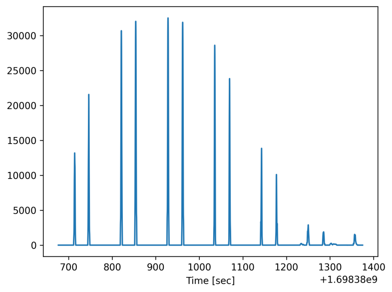


Figure 5: Moon TOD from an SAT

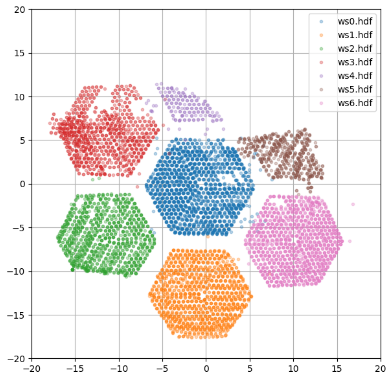
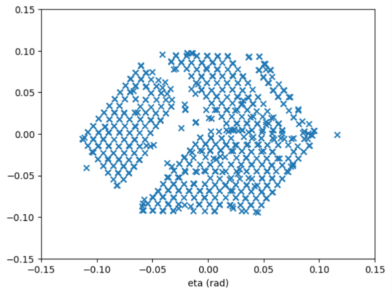


Figure 6: Raw pointing fits (from T. Terasaki)

Focal Plane for Mapmaking

Some issues with using raw fits:

- Incomplete focal planes
- Outliers and ghosts
- Poor sampling leads to odd features
- How do we effectively combine multiple fits?



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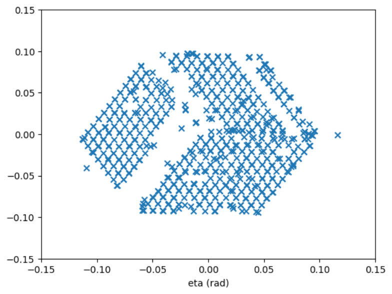

Figure 7: Raw pointing fits

We need to construct a focal plane that is clean and complete. Current approach is to fit a template against the raw fits for this.

Generating Templates

All our optics are already modeled from the design stage

$\rightarrow$ We can use this as a template for our fit focal planes

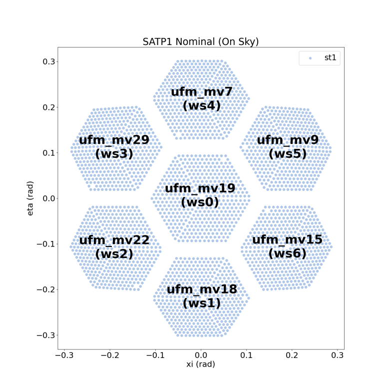

Figure 8: SATp1 Template

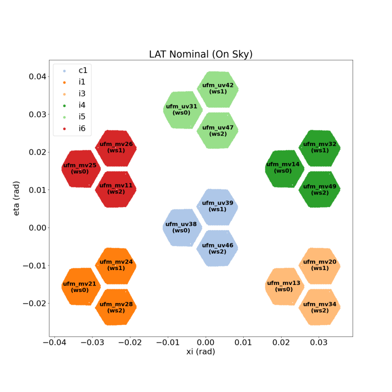

Figure 9: LAT Template

The Affine Transformation

A simple rotation and shift was not able to capture what we see

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We use two methods to compute A:

- Singular value decomposition (SVD) based, good at dealing with a small but unknown outlier population
- Weighted least squares, also allows you to fit for b simultaneously

Code for this kind of work: skhrg/megham

Constructing The Focal Plane

For each fit result:

1. Reject ghosts and outliers
2. Initial alignment to template using the SVD
3. Compute a gaussian weight for each detector using $\sigma = \frac{template\_spacing}{weight\_factor}$
4. Compute weighted average position for each detector
5. Compute a weighted transformation from the template for each array
6. Decompose A to pull out the common mode that all arrays see

Now we have a "noise free" focal plane for mapmaking and transformation parameters to construct the pointing model

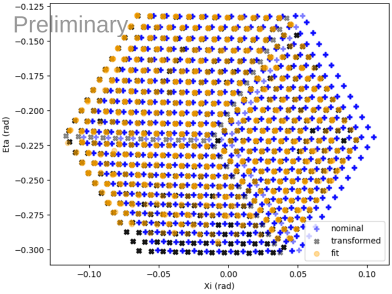

Figure 10: Focal plane with fit template

Is This Good Enough?

Still an open question if the affine transformation is enough to capture the difference between the template and reality.

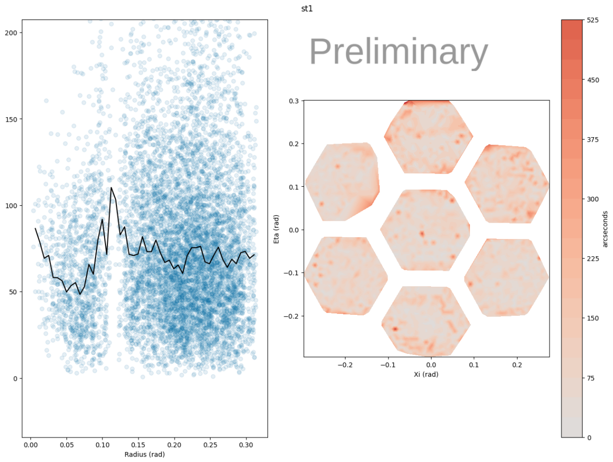

Figure 11: Fit focal plane residuals (preliminary result with limited data)

Looking At Residuals

Detailed looks at the residuals can help improve our templates and figure out which arrays need more data

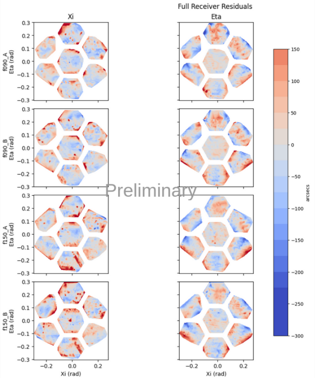

Figure 12: Before a template fix

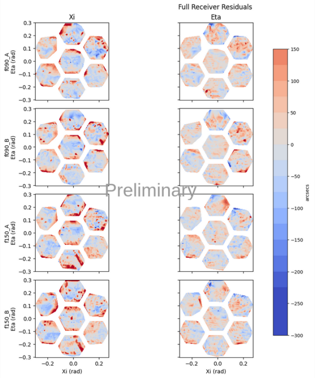

Figure 13: After a template fix

Residuals above are preliminary results with limited data.

But The Maps Look Nice

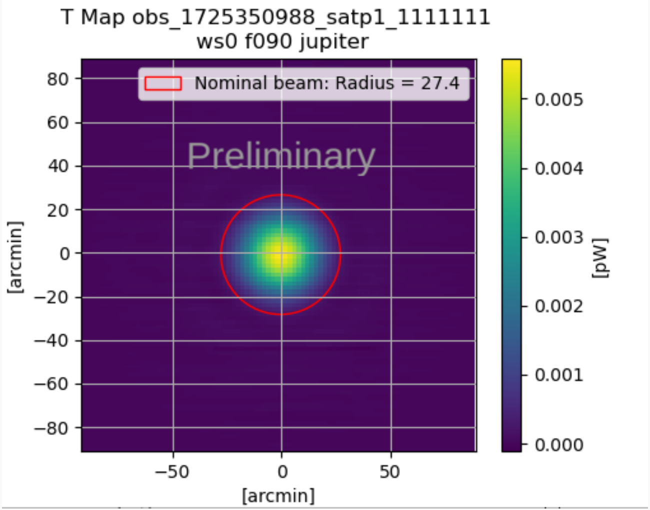

Figure 14: Beam map with template fit pointing (from R. Gerras, using code based on code from T. Alford)

Feedback Loop

On top of feeding back to the template generation we also form a feedback loop with the pointing model.

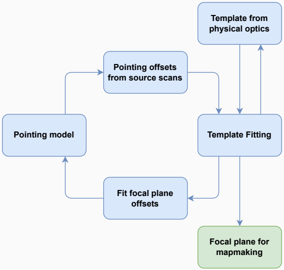

Figure 15: Flowchart of feedback loop

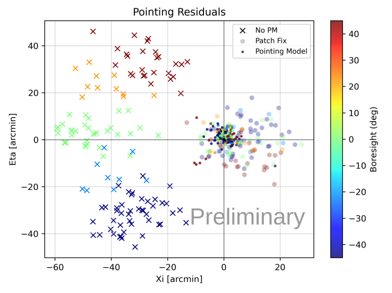

Figure 16: Improvement of residuals with pointing model (from E. Shaw)

Bonus: We Can Do This Without A Detector Map

Template fitting is just a form of point-set registration

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Joint CPD

- Take D sets of associated point clouds (ie: spatial coordinates and spatially correlated detector parameters)
- Treat each point in the point clouds being fit as a gaussian
- Optimize over the following objective function:

$$Q = -\sum_{n=1}^{N}\sum_{m=1}^{M} P^{old}(m|x_n)\log\left(P^{new}(m)p^{new}(x_n|m)\right)$$

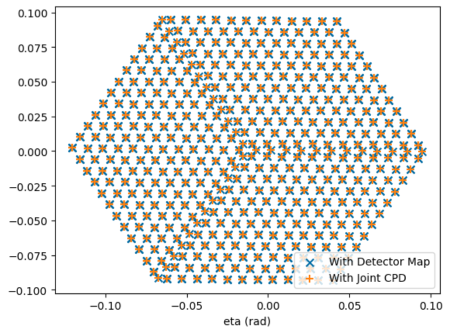
- Expanded and derive Q with respect to A and b

$\rightarrow$ we have an analytic form for the transform that can be iterated until convergence!

Full explanation of the math here

Bonus: And It Works (Sometimes)

When we have ok fits for most of the focal plane and outliers removed the template fit with Joint CPD is in perfect agreement with one with using the detector map!



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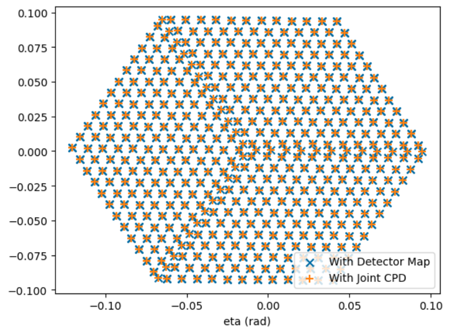

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But this method is far more susceptible to errors from bad data

Thank You

1