Pointing Refinement of SIRTF Images

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Preliminaries

- The Space Infrared Telescope Facility (SIRTF) contains three focal plane instruments: **IRAC** (imaging at 3.6, 4.5, 5.8, 8.8 μm), **MIPS** (imaging at 24, 70, 160 μm) and **IRS** (spectroscopy at 5.3? 37 μm).

- <u>Pointing Requirements:</u>
  - The observatory (main bore-sight alone) will provide pointing and control of at least 5" absolute accuracy with 0.3" stability over 200 sec (1s radial).
  - The star-tracker/bore-sight assembly shall produce image data with an a-posteriori pointing knowledge of 1.4" (1s radial) in the ICRS (International Celestial Reference System) frame over the entire field of view for imaging.

- <u>The end-to-end pointing accuracy is a function of:</u>
  - The inherent star-tracker accuracy.
  - How well the star-tracker bore-sight is known in the telescope bore-sight (science instrument frame).
  - Variations in the latter due to thermo-mechanical deflections between pointing control reference sensors in the focal plane and the star tracker.

Goals, General Overview

- Why refine the pointing?
  - Co-align frames in a common reference frame for robust Image co-addition and mosaic generation.
  - This will enable source extraction and position determination to faint levels.
  - When refined in an absolute (celestial) reference frame, can cross identify extracted sources with other catalogs.

- Our goal is to produce science products with sub-arcsecond pointing accuracy in the ICRS.

- Inputs to the SSC pointing refinement software "**POINTINGREFINE**" are point source positions and fluxes extracted from a mosaic of overlapping images acquired in a single wavelength band.

- Prior to source extraction and refinement, all input images are pre-processed for instrument artifact removal and raw pointing data corrected for systematic boresight-instrument array misalignment.

- The software uses the point source content in overlapping image frames to find a "global mimimization" of all relative offsets amongst all images in the mosaic. These offsets are used to refine the pointings.

- **POINTINGREFINE** can refine the pointings and orientations of SIRTF images in either a "relative" sense where pointings become fixed relative to a single image of a mosaic, or, in an "absolute" sense (in the celestial frame) if absolute point source information is known.

Software Processing Steps

If given *x*, *y* positions of extracted point sources only, transform to RA, Dec to perform source matching.

Point source position and flux matching between all possible frame pairs in input list (including absolute reference if specified).

Define **reference image frame** – for absolute refinement this is a "fiducial frame" encompassing all images of the mosaic.

Transform correlated point source positions and uncertainties to reference-image frame.

Set up global minimization computation between all overlapping images.

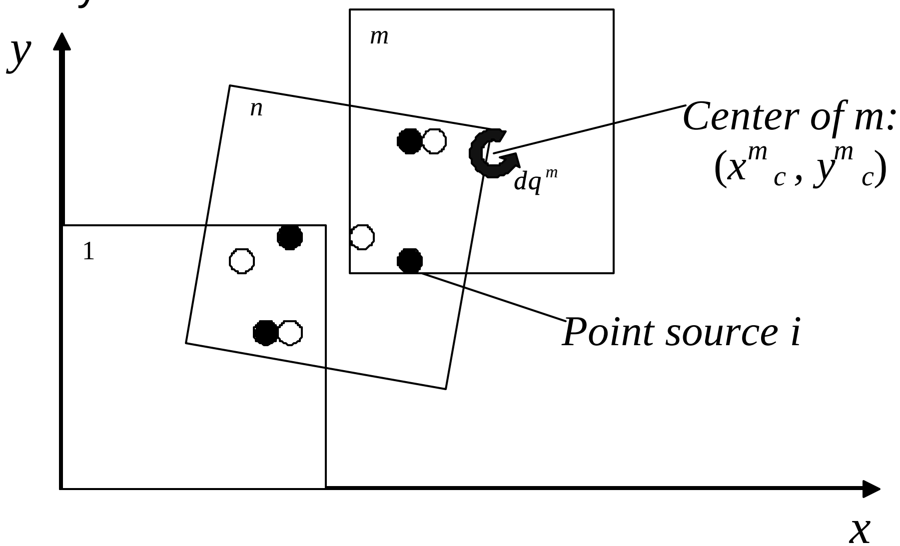
Solve linear matrix equation for translational and rotational offsets in (mosaic) reference image frame for each image and compute full error-covariance matrix.

Apply offsets to *x*,*y* pointing centers of all images. Transform to RA, Dec to obtain refined celestial pointings and twist angles.

Results output: Write new refined pointing keywords to FITS headers and optionally output table file and diagnostic information.

Method

- Consider the simple three image mosaic below where image 1 defines the "fiducial" reference frame. The circles are point sources detected from each overlapping image pair transformed into the fiducial reference frame. They are slightly offset to mimic the presence of pointing uncertainty.



- The coordinates of a correlated point source common to an image pair are related by:

$$x_i^m \rightarrow \tilde{x}_i^n = x_i^m - (y_i^m - y_c^m)dq^m + dX^m$$

$$y_i^m \rightarrow \tilde{y}_i^n = y_i^m + (x_i^m - x_c^m)dq^m + dY^m$$

where $d?^m$, dX^m, dY^m are Cartesian offsets and we have made the approximation *sind?* ≈ *d?* ; *cosd?* ≈1 since uncertainties in measured twist angles are expected to be small (≤ 20").

Method

- We define a cost function *L* representing the sum of the squares of the "corrected" differences of all point source positions in all possible overlapping imaging pairs:

$$L = \sum_{m,n} \sum_{i} \left\{ \frac{1}{\Delta x_i^{m,n}} \left[\tilde{x}_i^n - \tilde{x}_i^m \right]^2 + \frac{1}{\Delta y_i^{m,n}} \left[\tilde{y}_i^n - \tilde{y}_i^m \right]^2 \right\}$$

where

$$\Delta x_i^{m,n} = s^2(x_i^m) + s^2(x_i^n)$$
$$\Delta y_i^{m,n} = s^2(y_i^m) + s^2(y_i^n)$$

and the s^2 represent variances in <u>extracted point source positions.</u>

- We minimize the function *L* with respect to all offsets for all images *m:* $d?^m$, dX^m, dY^m where *m* represents an image containing point sources in common with another image.
- At the <u>global minimum</u> of *L*, we have the following conditions hold:

$$\frac{\partial L}{\partial dq^m} = 0, \qquad \frac{\partial L}{\partial dX^m} = 0, \qquad \frac{\partial L}{\partial dY^m} = 0$$

Method continued..

- Evaluating the partial derivatives on the previous page leads to a set three simultaneous equations for each image in our mosaic. In general, for ***N*** correlated images, we will have

$$3(N-1)\,\text{simultaneous equations in } 3(N-1)\,\text{unknowns}$$

- Why the "–1" ? Because we exclude the reference image frame which by definition has $d?^m = 0$, $dX^m = 0$, $dY^m = 0$. This is a constraint in the global-minimization computation.

- The 3(N–1) system of simultaneous equations can be solved using a linear sparse matrix solver. In particular, we use the UMFPACK library adapted for solving unsymmetric sparse linear matrix equations (T. A. Davis, 2002).

- If absolute source positions are known, these will form part of the "fiducial" image frame encompassing the entire mosaic. This image can be treated in the normal way like a single input image.
    - When input images become refined "relative" to this fiducial reference, they in reality become "absolutely" refined.
    - The inclusion of absolute point sources also reduces the effect of "random walk" in offsets uncertainties with distance if a single isolated reference image were chosen.

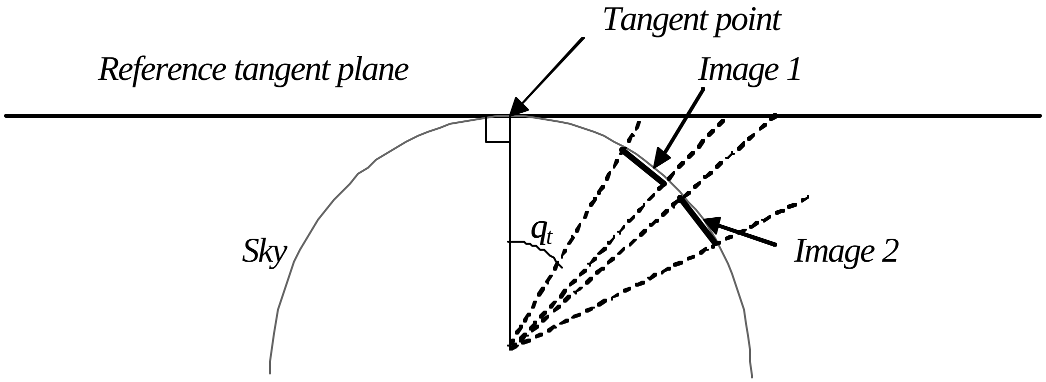
Method continued..

- Once Cartesian offsets in the reference image frame are computed, the pointing centers are corrected and transformed back to the sky to yield "refined" pointings:

$$\left.\begin{aligned} x_c^m(\text{new}) &= x_c^m(\text{old}) + dX^m \\ y_c^m(\text{new}) &= y_c^m(\text{old}) + dY^m \end{aligned}\right\} \rightarrow RA_{refined}, Dec_{refined}$$

- Image twist angles (or position angles) are refined in a similar manner, but this time using two fiducial reference points per image.

- One-dimensional representation of projection geometry: Mosaic size limitation is ? ≤ 5° above which projected offsets become non-linear (difference is ~ 1.5% at this limit).



Refinement of IRAC Images

- We plan to perform absolute refinement of IRAC images using the Two-Micron All Sky Survey (2MASS) catalog. The pointing accuracy of SIRTF is on the order of the IRAC pixel size (1.2”). It would be desirable to refine the pointing to sub-pixel accuracy.

- The 2MASS catalog covers the entire sky and its longest wavelength (2.2 μm) is similar to IRAC’s shortest wavelength band (3.6 μm). The catalog has a completeness limit of K = 14.5 mag which is bright enough that IRAC will always detect sources.

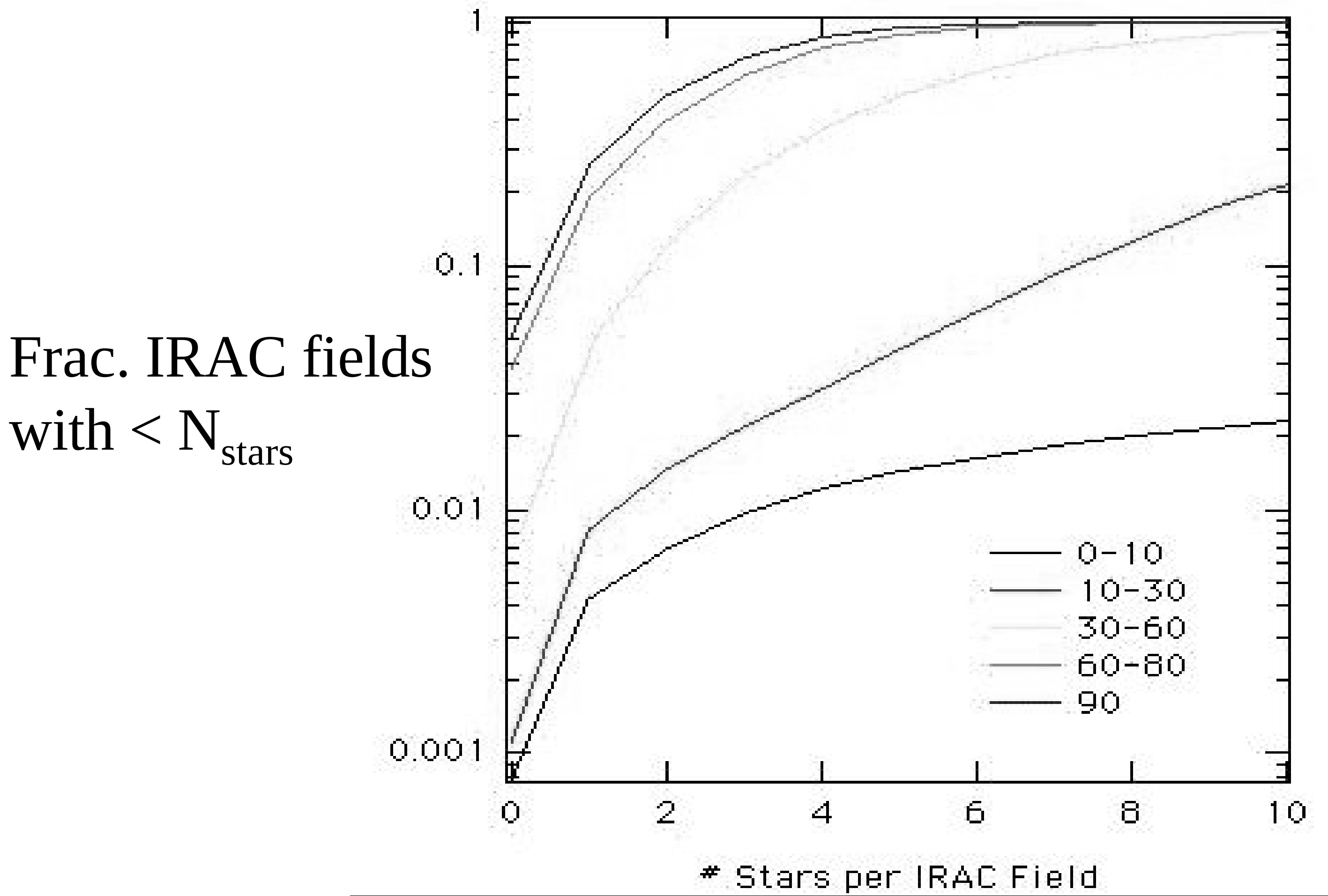
- 2MASS stars have a positional accuracy on the order of 0.15” which given the PSF size, is the best positional accuracy we could hope to achieve.

- The 2MASS stellar density is high enough that there is a high probability of finding sources within any given 5’ x 5’ IRAC field.

- IRAC performs simultaneous imaging at four wavelength bands. The 3.6 and 4.5 μm bands image adjacent areas of sky. This provides the advantage of doubling the search area and allowing simultaneous refinement of all IRAC bands since all FOV hardware offsets are known.

2MASS Statistics for IRAC

- Cumulative distribution as a function of 2MASS stellar density (courtesy of Jason Surace).



IRAC Pointing Refinement Simulation

- Simulation Steps:

1. Simulated a mosaic consisting of 800 IRAC (3.6 μm) "truth" FITS images with NO pointing uncertainties. Image overlap coverage was on average about 50%.

2. Made a second set of images with random pointing uncertainties added to all pointing FITS keywords. Pointing uncertainties were drawn from a Gaussian distribution with mean radial uncertainty $<\delta> \approx 1.4''$.

3. Made a list of "absolute" point sources by extracting the brightest (with centroid errors < 0.15 pixels) from each "truth" (noiseless pointing) image.

4. Made a fiducial reference image frame encompassing the entire mosaic and containing the randomly distributed "absolute" sources.

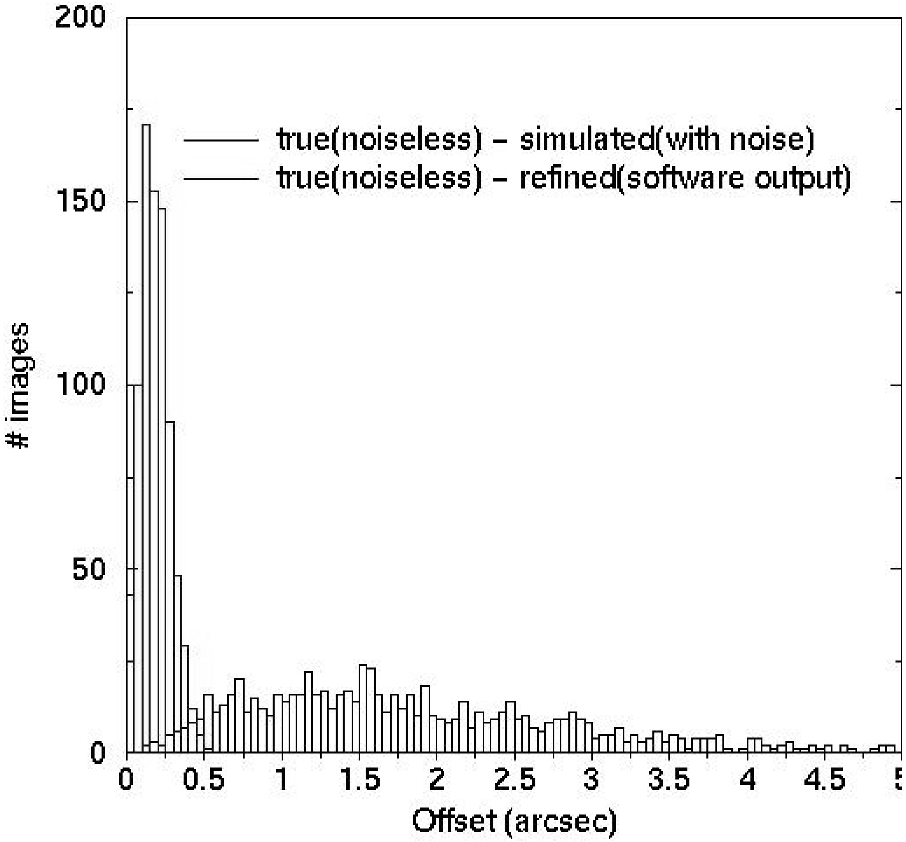
5. Ran the SSC source extractor on all input (with pointing uncertainty) images.

6. Ran the POINTINGREFINE software with inputs: source extraction lists, fiducial reference frame parameters and abspolute source list.

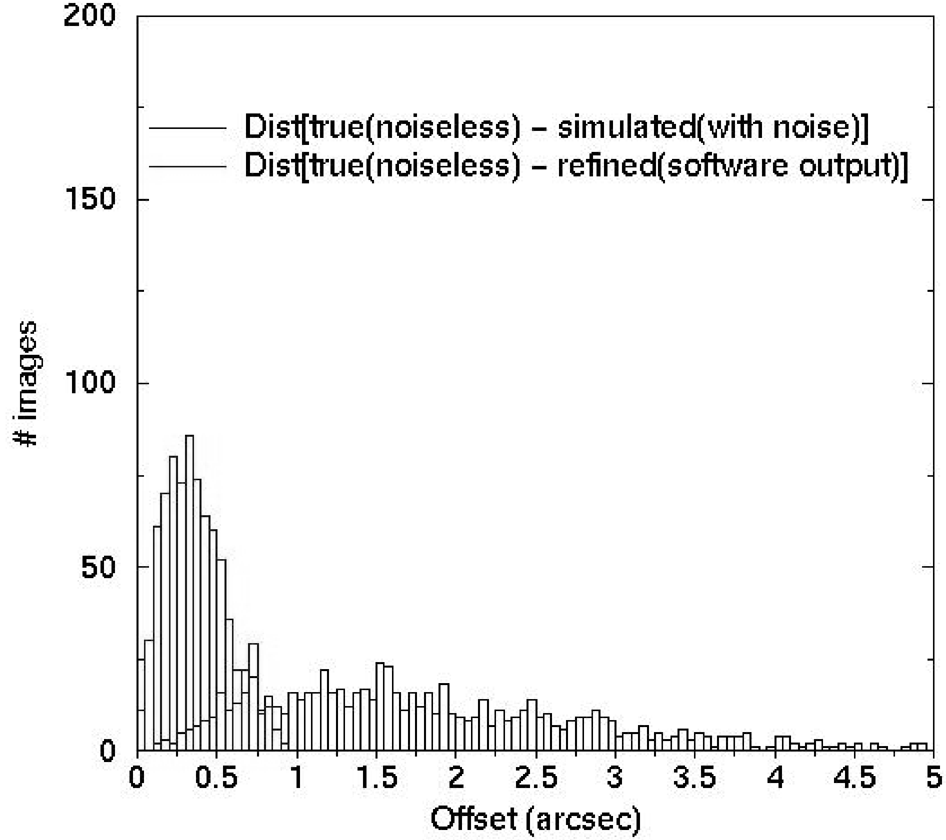
7. Compared distributions of radial distances between "true" (noiseless) pointings and refined (software output) pointings with simulated values.

IRAC Pointing Refinement Simulation

- ~15 absolutes per image
- ~ 50 extractions per image, with centroinding < 0.5 pixels

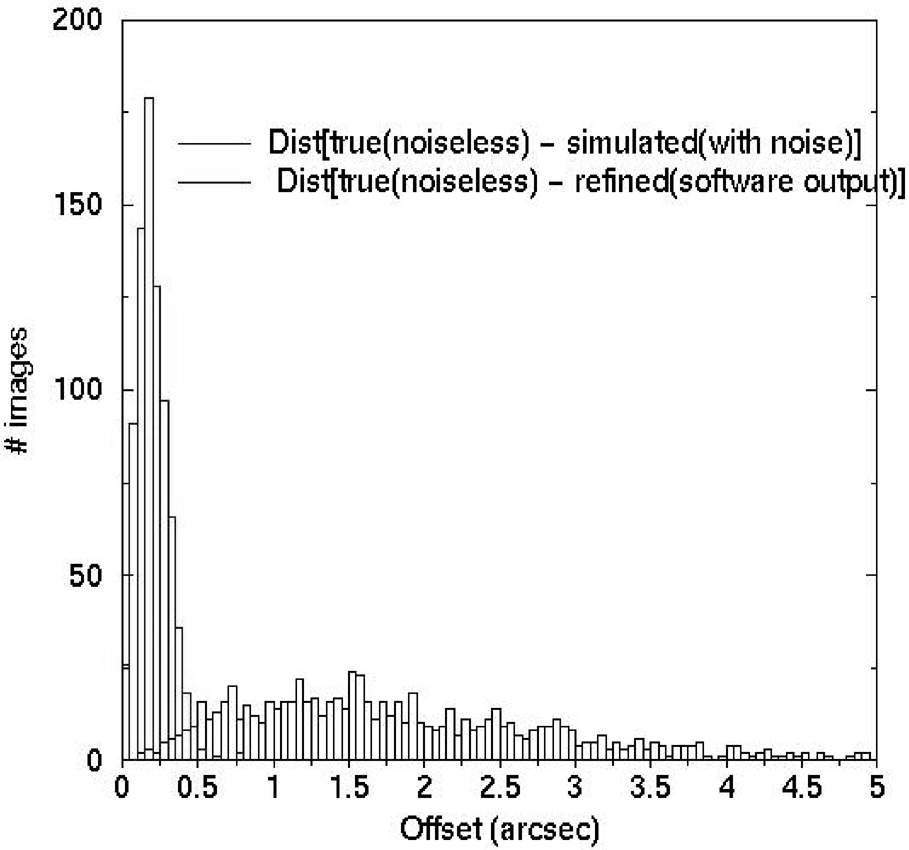


- ~80/800 absolute fraction (10%)
- ~ 50 extractions per image, with centroinding < 0.5 pixels

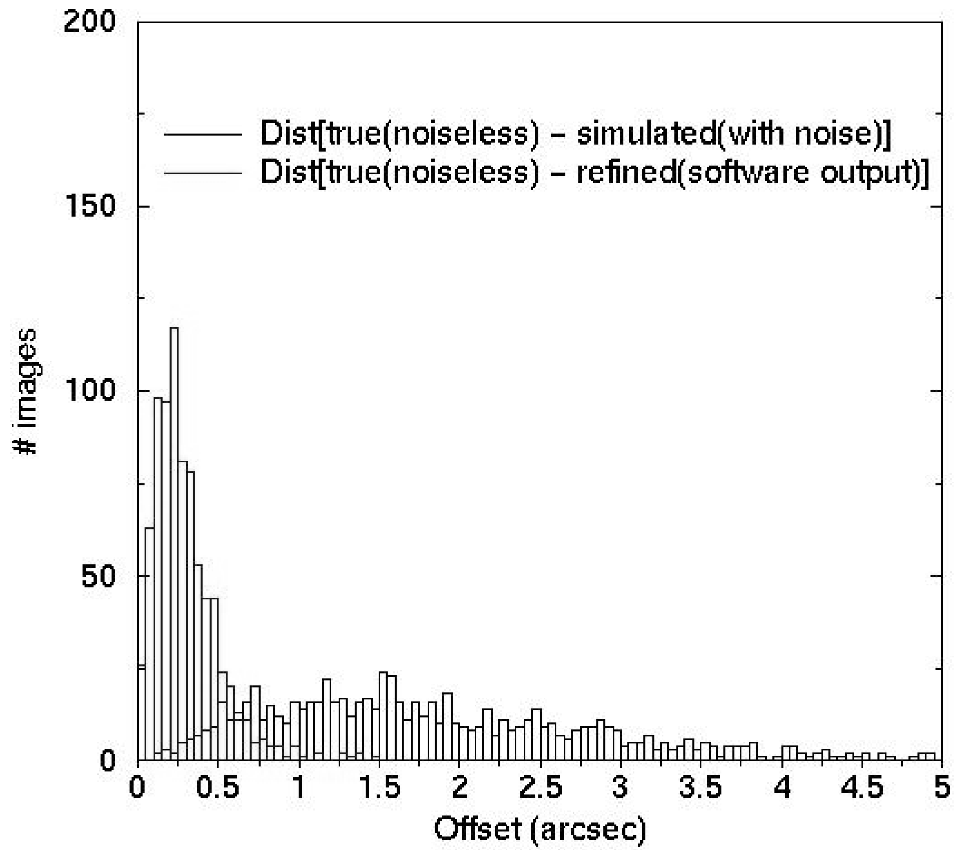


Refinement of IRAC Images

- ~560/800 absolute fraction (70%)
- ~ <u>50 extractions per frame</u>, <u>with centroinding < 0.5 pixels</u>



- ~560/800 absolute fraction (70%)
- ~ <u>10 extractions per frame</u>, <u>with centroinding < 0.3 pixels</u>



Conclusions and Summary

- The SIRTF Science Center's pointing refinement software uses a robust generic algorithm which will run in a lights-out fashion during operations.

- It can be used on any set of single wavelength FITS images. It's only dependence is the source extraction output table format generated by the SSC source extractor.

- Absolute refinement of individual FITS images is also supported. A list of mosaiced images need not be specified. It operates on either *x,y* pixel extractions or RA, Dec extractions.

- Main limitation in our current simulations is the lack of better determined PSFs to reduce centroiding errors in source extractions. The best we can do now is < 0.3 of a pixel at the expense of having too few sources to perform robust refinement.

- We expect source extraction centroids better than 1/10 of an arc-second with better sampled PSFs. Together with our conservative estimates of 2MASS detections and expected point-source densities, sub-arcseond absolute pointing accuracy for the IRAC arrays is very likely.

- Further documentation is available upon request (e-mail: fmasci@ipac.caltech.edu)