Pointing Refinement of SIRTF Images

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Abstract. The soon-to-be-launched Space Infrared Telescope Facility (SIRTF) shall produce image data with an a-posteriori pointing knowledge of $1.4''$ (1σ radial) with a goal of $1.2''$ in the International Celestial Reference System (ICRS). To perform robust image coaddition, mosaic generation, extraction and position determination of faint sources, the pointing will need to be refined to better than a few-tenths of an arc-second. This paper summarizes the pointing-refinement algorithm and presents the results of testing on simulated data.

1. Introduction

One of the goals of astronomical image data acquisition is to infer the pointing in an absolute coordinate system as accurately as possible, in this case the celestial reference system. Instabilities in telescope pointing and tracking however inhibit us from achieving this goal. SIRTF for instance, is expected to provide pointing and control of at least $5''$ absolute accuracy with $0.3''$ stability over 200 sec (1σ radial). In the ICRS, the star-tracker assembly provides an a-posteriori pointing knowledge of $1.4''$. The end-to-end pointing accuracy is a function of the inherent star-tracker accuracy, the spacecraft control system, how well the star-tracker bore-sight is known in the focal plane array (instrument) frame, and variations in the latter due to thermo-mechanical deflections. The SIRTF observatory will have a data flow rate of $> 10,000$ science images per day. This will require an automated, self-consistent means of refining the celestial pointing as robustly as possible.

The conventional method to refine the pointing is to make comparisons of astrometric sources with positions known to better than a few percent of the observed positional errors. The primary motivation for pointing refinement is to enable robust coaddition of image frames in a common reference frame so that source extraction and position determination to faint flux levels can be performed. Moreover, refinement in an absolute (celestial) reference frame will enable robust cross-identification of extracted sources with other catalogs.

For these purposes, we have developed a stand-alone software package "*pointingrefine*" with a goal to generate science products with sub-arcsecond pointing accuracy in the ICRS. The software 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 ICRS) when absolute point source information is known.

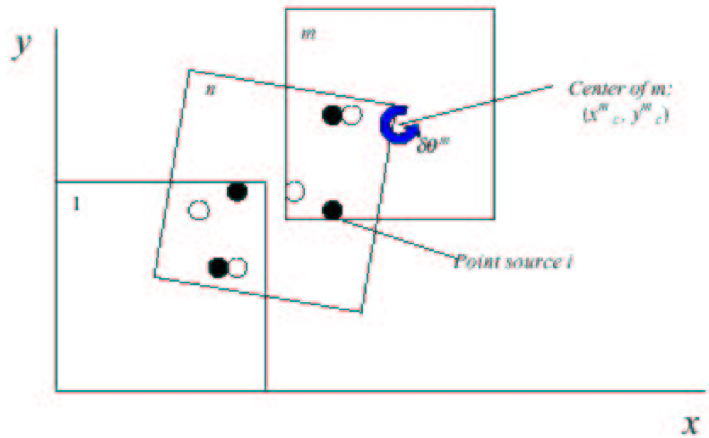

Figure 1. A simple three image mosaic.

2. Software Summary

As part of routine pipeline operations at the SIRTF Science Center (SSC), all input images are pre-processed for instrument artifact removal and pointing data attached to raw FITS images. Following this, point source extraction is performed on individual frames for input into *pointingrefine*. The software expects point source lists adhering to the format produced by the SSC source extractor. The *pointingrefine* software performs the following:

1. Reads source extraction tables, FITS images from input lists and if absolute refinement is desired, a list of absolute point source positions.
2. Point source position and flux matching is performed between all possible image pairs in the input list. This includes absolute point sources if available.
3. Transform correlated point source positions and uncertainties to a Cartesian fiducial (mosaic) reference frame.
4. Set up global minimization equations involving relative offsets between all correlated point source positions.
5. Solve a linear matrix equation for translational and rotational offsets in mosaic reference frame for each input image and compute the full error-covariance matrix.
6. Apply these offsets to the pointing centers (x_c, y_c) of all images. Transform to RA, Dec to obtain refined celestial pointings and orientations.
7. Results output: Write new refined pointing keywords to FITS headers and to a table file with diagnostic information.

3. Algorithm

A brief outline of the refinement algorithm (primarily steps 4, 5, and 6 above) is as follows. Consider the simple three image mosaic in Figure 1. Image "1" defines the "fiducial" reference frame. The circles represent point sources detected from each overlapping image pair transformed into the fiducial frame. The filled circles are sources extracted from image n and the open circles are sources extracted from either image 1 or m. The correlated source pairs are slightly offset from each other to mimic the presence of pointing uncertainty in each raw input image. The Cartesian coordinates of a correlated point source common to an image pair are related by:

$$
\begin{aligned}
x_i^m \to \tilde{x}_i^n &= x_i^m - (y_i^m - y_c^m)\delta\theta^m + \delta X^m \\
y_i^m \to \tilde{y}_i^n &= y_i^m - (x_i^m - x_c^m)\delta\theta^m + \delta Y^m,
\end{aligned}
\tag{1}
$$

where $\delta\theta^m$, δX^m, δY^m are rotational and Cartesian offsets respectively in the fiducial mosaic frame. We have made the approximation $\sin\delta\theta \approx \delta\theta$ ($\cos\delta\theta \approx 1$) since uncertainties in measured position angles are expected to be small ($\lesssim 20''$).

We define a cost function L, representing the sum of the squares of the "corrected" differences of all correlated point source positions in all overlapping image pairs (m,n):

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

where

$$
\begin{aligned}
\Delta x_i^{m,n} &= \sigma^2(x_i^m) + \sigma^2(x_i^n) \\
\Delta y_i^{m,n} &= \sigma^2(y_i^m) + \sigma^2(y_i^n)
\end{aligned}
\tag{3}
$$

and the σ^2 represent variances in extracted point source positions. The function L (Equation 2) is minimized with respect to the Cartesian offsets ($\delta\theta^m$, δX^m, δY^m) for an image m which contains point sources in common with all other images n. At the global minimum of L, the following conditions hold:

$$\frac{\partial L}{\partial\delta\theta^m} = 0;\ \frac{\partial L}{\partial\delta X^m} = 0;\ \frac{\partial L}{\partial\delta Y^m} = 0. \tag{4}$$

Evaluating these partial derivatives leads to a set of three simultaneous equations for each image in our mosaic. In general, for N correlated images, we will have $3(N-1)$ simultaneous equations in $3(N-1)$ unknowns. It is "$N-1$" because we exclude the reference image frame which by definition has the constraint $\delta\theta^m = \delta X^m = \delta Y^m = 0$. The $3(N-1)$ system of equations can be solved using linear sparse matrix methods since a large number of the matrix elements will be zero. We use the UMFPACK[1] library which is adapted for solving large unsymmetric matrix systems.

When absolute astrometric references are available, the "fiducial" reference image (mosaic) frame is treated like a single input image, which contains the *absolute* point source positions. When the input images become refined relative to this fiducial image, they in reality become *absolutely* refined (in the ICRS). The presence of absolute point sources also reduces the effect of "random walks"

[1] http://www.cise.ufl.edu/research/sparse/umfpack/

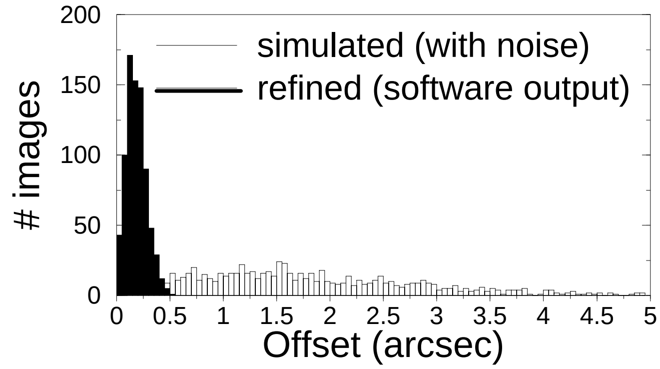

Figure 2. Distribution of radial offsets between "true" (noiseless) and simulated pointings (with noise) - *broad histogram*, and between true and refined pointings - *narrow histogram*.

in offset uncertainties with distance if a single input image were chosen as the reference instead. Once Cartesian offsets ($\delta\theta^m$, δX^m, δY^m) in the reference (mosaic) frame are computed, the pointing centers (x_c, y_c) are corrected (by use of Equation 1) and transformed back to the sky to yield refined pointings. Image orientations are refined in a similar manner, but in this case, we need to transform at least two fiducial points per image to uniquely determine the orientation.

4. Simulations

The Infrared Array Camera (IRAC) on SIRTF will perform simultaneous imaging at four bands spanning the range $\approx 3.6\mu m$ to $8\mu m$. Each array consists of 256×256 $1.2''$ pixels. We simulated a mosaic of 800 IRAC ($3.6\mu m$) "truth" images (i.e. *with no* pointing error) with each image containing randomly distributed point sources. Input image overlap coverage was $\sim 50\%$. A second set of 800 images was simulated with random errors added to the pointing keywords of image headers. The errors were drawn from a Gaussian distribution with mean radial error $\langle\delta\rangle \approx 1.4''$. An absolute point source list was also simulated by extracting the brightest sources with smallest centroiding errors from each "truth" image. The average number of "absolutes" per input image was 10. The SSC point source extractor was then used to extract ≈ 50 point sources from each input image (with pointing error).

Figure 2 shows the results of our simulation where we compare the distributions of radial offsets relative to "truth" pointings before and after refinement. The refinement is better than 85% for almost every image. The main limitation is full knowledge of the Point Response Function (PRF) to reduce centroiding errors in source extractions. However, we expect extraction centroids better than $0.1''$ with better sampled PRFs. This will give us the sub-arcsecond absolute pointing accuracy sought in SIRTF's imaging detectors.

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