THE 2MASS POINT SOURCE PROCESSING PIPELINE: DESIGN AND PROTOTYPE RESULTS

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1. Introduction

The Two Micron All Sky Survey will begin operations in the spring of 1997 (Skrutskie *et al.*, this volume). The Infrared Processing and Analysis Center (IPAC) is tasked with processing ~30GB of data that will be obtained each night by the northern and southern telescopes during the survey. The goal of this processing is to produce three primary data products: 1) the 2MASS Image Atlas that will contain $\sim10^6$ 512x1024 ($1''$/pix) images in J, H and K_s, 2) the 2MASS Point Source Catalog containing accurate astrometry and photometry for $\sim10^8$ point sources, and 3) the 2MASS Extended Source Catalog that will contain accurate positions, photometry and morphological information for $\sim10^6$ small extended sources.

The 2MASS Production Processing System (2MAPPS) is being designed and implemented at IPAC. This system will exploit 2MASS's innovative data acquisition techniques to produce image, point and extended source data that meets or exceeds the completeness, photometric and astrometric requirements of the survey (Skrutskie *et al.*, this volume). In this paper, we present a brief overview of 2MAPPS with the emphasis on point source processing. We describe in detail the innovative solutions that have been developed for position reconstruction and point source photometry, and present illustrative results from prototype pipeline processing of single channel 2MASS prototype camera data.

2. 2MAPPS Point Source Processing Overview

Table 1 shows the basic components of point source processing within 2MAPPS. Data from each 6^o 2MASS "scan" are processed as a unit, with the J, H and K_s frames processed in parallel. In general, data processing

TABLE 1. 2MAPPS Point Source Processing Steps and Products

PROCESS	PRODUCT
0. Input	Raw R1 and R2 data frames, dark frames, twilight sky frames
1. Instrumental Calibration	"Flattened" R1 and R2 frames
2. Detect sources in R1 and R2 frames	R1 and R2 source positions, R1 photometry
3. Position Reconstruction	Frame offsets, preliminary astrometric solution
4. Combine R2 frames	IMAGE ATLAS (1.0″/pix)
5. Detect R2 sources in Coadded Images	R2 detection list, positions
6. Point source photometry	R2 Photometry, improved positions, psf-fit data
7. Photometric Calibration	"Final" point source lists, positions, photometry

within 2MAPPS is a linear process with the output of each step being the input for each subsequent step. Iterations are held to a minimum for efficiency. Below are brief descriptions of each phase of the processing.

Input Data The processing pipeline is provided with the raw frame data for dark measurements, twilight sky observations, and both the first 0.05s read (R1) and second 1.3s exposure read (R2) from the survey and photometric calibration measurements. In addition, the observatory provides log files describing the nights observations and data tape contents.

Instrumental Calibration Dark frames are subtracted from all sky frames, twilight-sky multiplicative gain corrections (flat-fields) and additive local sky offset corrections are evaluated and applied to each survey frame. This produces final "flattened" R1 and R2 frames.

Preliminary Source Detection Individual R1 and R2 frames are convolved with matched zero-sum gaussian filter, and sources are detected where they exceed a signal-to-noise threshold. Source centroids and aperture photometry are extracted.

Position Reconstruction Use R1 and R2 source positions from frames to determine self-consistent solution for frame-to-frame offsets, and relationships between three band coordinate system. Evaluate an astrometric solution that maps instrumental coordinates to J2000 RA and DEC.

Combine R2 Frames Use the frame-to-frame offsets evaluated in the position reconstruction step to register and combine six R2 frames covering each point on the sky, and resample the combined images to $1''$/pixel. The resulting 512x1024 pixel images comprise the 2MASS Image Atlas.

Source Detection in Coadded Images Carry out a similar threshold detect process as described in step 2, but operate on gaussian filtered coadded R2 images. This allows detection of the faintest sources.

Point Source Photometry Perform profile fitting photometry on sources detected in step 5, but *operate on individual frames*. This allows optimal use of frame-to-frame dithering to extract improved source positions, and the best bad pixel and cosmic ray rejection.

Photometric Calibration and Corrections Identify and remove sources associated with known instrumental artifacts such as persistence, diffraction spikes, etc. Also, combine R1 source positions and aperture photometry from step 2. Apply photometric calibrations to R1 and R2 data (extinction and zero-point corrections). These represent the final photometric and astrometric characterization for point sources.

3. Astrometry in 2MAPPS

Position reconstruction for point sources in 2MAPPS is in principle a simple two-step process. First, objects detected in the 260 frames comprising a scan are tied together on a common coordinate system using the frame-to-frame positional offsets, and second, that scan coordinate system is mapped onto an inertial J2000 coordinate system on the sky defined by reference stars from the Tycho Catalog. In reality, however, these "simple" steps are complicated by mechanical and environmental factors.

3.1. "ASSEMBLING" THE SCAN

Small errors in telescope motion due to drive gear imperfections and windshake will cause the offsets between frame centers to vary slightly along a 2MASS scan. Therefore, to connect the frames in a scan, the frame-to-frame offsets must be measured continuously using stars in the frame overlap regions. The relative positions of sources on individual data frames can be determined with an accuracy $\sigma_f \sim$0.1-0.2$''$. The small uncertainty in the positions of each star implies that the relative positions of frame centers can only be measured to a finite accuracy. As a consequence, a random-walk error in the frame offsets will accumulate along the scan. The total uncertainty with respect to the center of the first frame accumulated over a scan containing N_f frames is approximately:

$$\sigma_{tot} = \sigma_f N_f^{1/2} (5 n_s)^{-1/2}$$

where σ_f is the single object centroiding accuracy, n_s is the number of stars in the overlap region (6-7 on average in R2 frames), and the factor of 5 comes from the correlation of a given star appearing in six consecutive frames. A 2MASS six degree scan contains 260 frames, so the accumulated uncertainty in one band is 0.7-1.4$''$- far in excess of the 0.5$''$RMS positional accuracy requirement for 2MASS.

The frame offset error over a scan can be reduced by increasing the number of stars in the frame overlap region (n_s). At lower galactic latitudes, increasing star density accomplishes this. However, at high latitudes, the star density is dangerously low, and n_s can drop to zero.

An elegant solution to the low star density problem has been developed that takes advantage of the three bands of correlated data obtained by 2MASS, and the two images obtained of each field in each band (R1 and R2). A moderately bright star ($9 \leq K_s \leq 13$) can appear in up to 36 2MASS frames (R1+R2)*(J+H+K_s). Using all apparitions of all stars, a set of coupled equations are solved to provide a *self-consistent* solution for the offsets of all frames in a scan, as well as the interrelationship between the positions of sources in each band, and any effective focal plane distortion due to differential refraction or camera flexure. The value of n_s can be increased way by factors of up to 36. On average the gain is $\sim$6, which still reduces the accumulated random walk errors over a scan to 0.2-0.4$''$.

3.2. MAPPING THE SCAN ONTO THE SKY

The amplitude of the relative frame offset error is further reduced in 2MAPPS by effectively reducing the random walk length - the number of frames over which the error can accumulate in a scan (N_f). This is accomplished by "pinning" the scan at several locations using Tycho astrometric reference stars. The separations of Tycho stars within a scan fix the positional offsets of the frames in which they lie to a high degree of accuracy. Therefore, the random walk error can propagate over only 1/2 of the distance between the fixed frames. On average, there are $\sim$18 Tycho reference stars in 2MASS scans, so the random walk length is reduced to approximately 7-8 frames. While the distribution of Tycho stars within a scan ultimately dictates the frame-offset error, the average error will be reduced to 0.04-0.07$''$using this technique. At the galactic poles, there are fewer Tycho stars per scan, but in the worst cases the average relative frame offset error is 0.1-0.2″, well within the astrometric requirements of the survey.

In practice, the use of Tycho stars in evaluating the frame offsets is integrated into the global solution using the data from all three bands, and both reads. The result is that all of the extracted sources are mapped onto a common scan coordinate system that is simultaneously mapped into the inertial J2000 coordinate system defined by Tycho. The final astrometric solution is applied to all sources and to the Image Atlas data.

4. 2MAPPS Photometry Overview

Photometry of most point sources in 2MASS is carried out using a *profile fitting algorithm* on the 1.3s R2 frames. Profile fitting is used because it provides improved signal-to-noise measurements for fainter sources, an optimal use of the sub-pixel dithering strategy to derive better positions, a more robust measurement of both flux density and position in crowded regions, and better rejection of bad pixels and cosmic ray events for unbiased photometry.

Photometry of the brightest sources observed by 2MASS is performed on the 0.05s R1 frames. Simple aperture photometry is applied to objects detected in these images.

4.1. PROFILE FITTING PHOTOMETRY

As outlined in Table 1, sources are *detected* in the gaussian filtered coadded R2 images (step 5) to provide the most sensitive detection list. Once a source is detected, however, it is actually *measured* in the stack of the six individual 1.3s R2 frames in which it lies.

For each detected source, a point source profile or template is fit by minimizing the combined χ^2 residuals between the fit and data from all six frames. The fitting procedure allows the x-y position and amplitude of the profile to vary with respect to the stack of six frames, *but not the relative positions of the six frames in the stack*. This is done because the relative positions of the frames have already been determined very accurately from the frame offsets, as discussed in Section 3. The value of the template amplitude (= source flux), the χ^2 goodness of fit, and the position are reported.

If the quality of the profile fit is poor (*i.e.* large value of χ^2), the photometry algorithm attempts to fit two or three profiles in an effort to determine a better fit.

4.2. POINT SPREAD FUNCTION DETERMINATION AND SEEING

The biggest challenge to accurate photometry in 2MAPPS is determining the correct point spread function (PSF) template to fit to the data. Mismatches between the template and true point source profiles lead to both offsets in the photometric scale, and increased dispersion in the photometry. Photometric offsets are relatively easy to correct by normalization to aperture photometry, but the increased dispersion cannot be corrected and can quickly drive the total photometric error budget beyond the requirements. For example, a difference of only $0.2''$between the template and true source widths leads to an additional 3-4% dispersion in the photometry.

The primary cause of PSF/data mismatch is rapid variation of the point source profile due to atmospheric seeing. In traditional CCD photometry, the PSF is measured carefully on each frame to be photometered using isolated, high signal-to-noise stars. Individual 2MASS data frames usually have too few high SNR stars to make reliable *in situ* PSF measurements and the large volume of data preclude selective measurements of any star. 2MAPPS will use the algorithm described by Schneider *et al.* (this volume) that needs only 10-15 stars to determine the point source profile accurately, to monitor seeing over several frames, on a 15-45s time interval depending on source density. When the PSF is accurately matched to the observed seeing, profile-fit photometry extracted from fields observed multiple times with the 2MASS prototype camera exhibits an RMS dispersion of only $\sim$2%.

4.3. PHOTOMETRIC CALIBRATION

Photometric zero points and extinction corrections in 2MASS will be evaluated from observations of pairs of calibration fields every $\sim$2 hours each night. A calibration observation will consist of six rapidly repeated 1^o scans of a field that contains one or more pre-existing photometric standard stars. After a short time, every star in the scan will become a tertiary standard star that has been exquisitely calibrated relative to the existing calibrator in the field.

As a result of discussion during this Conference, 2MASS and DENIS will adopt common calibration fields in the southern and equatorial sky. Because both surveys utilize similar NICMOS3 detectors, and identical J and K_s filters, this coordination will result in measurements on a common photometric system.

Figure 1. *(left)* 2MASS prototype camera image of a 8'x10' region around M67. Point sources detected and measured using the processing pipeline are identified with white dots. White crosses indicate objects associated with bright star persistence and other artifacts. *(right)* J-K_s color-magnitude diagram for point sources detected in the M67 field.

4.4. PROTOTYPE CAMERA POINT SOURCE PHOTOMETRY OF M67

A 2MASS prototype camera K_s image of the region around the Galactic Cluster M67 processed at IPAC with the prototype processing pipeline is shown in Figure 1. Point sources detected and photometered in this frame are marked with small superimposed points. A number of sources on the image are actually artifacts associated with the persistence of bright stars; these are indicated with crosses. Identification of these artifacts, as well as any associated with diffraction spikes and any other image artifact is a critical phase of correction for the final point source lists in 2MAPPS.

The quality of calibrated, profile-fit point source photometry produced by 2MAPPS is illustrated by the J and K_s color magnitude diagram of M67 also shown in Figure 1. Notice the well-defined main sequence, the main sequence turnoff at a J-K_s color corresponding to $\sim$F0 type, and the suggestion of the binary main sequence in this cluster.

5. 2MASS Point Source Science: The Search for Rare Objects

The nearly 200 deg^2 of sky that have been observed with the 2MASS prototype camera, and the quality of point source data processing at IPAC have enabled a number of pilot scientific studies. Two of these investigations involve the search for rare objects among the 2MASS point sources lists: very late M-dwarf stars, and red QSOs.

Kirkpatrick, Beichman and Skrutskie (1996) have searched 105 deg^2 covered during 1992-94 prototype camera observations for point sources with red IR colors (J-K_s $\geq$1.1) and/or red optical-IR colors (R-K_s $\geq$6.0). Spectroscopy of 8 of these red candidates has revealed that all are M-dwarfs with spectral type M6 or later. Six of the eight are $\geq$M7, increasing the number of known M7+ dwarfs by 35%. One of these objects, whose spectrum is compared with other representative cool dwarfs in Figure 2, has a preliminary classification of >M10V, making it the coolest isolated dwarf now know. Only GD165B and GL229B, both discovered as companions to known stars, are cooler. These results suggest that 2MASS will image and measure over 2700 M7+ dwarfs having K_s $\leq$14.0, thus determining the low-mass end of the local stellar luminosity function to unprecedented accuracy.

Cutri *et al.* (1995) have made a similar search for red point sources (J-K_s $\geq$1.3 and/or R-K_s $\geq$4.0) in the $\sim$100deg^2 observed during 1995 with the 2MASS prototype camera to search for red AGN/QSOs. Among the candidates observed spectroscopically, 10 are compact (*i.e.* unresolved to 2MASS) emission line galaxies with z$\sim$0.1-0.2. Four of these galaxies were detected in the field of M67, and appear to be part of a background cluster. One of the red 2MASS sources observed spectroscopically has been confirmed to be the first 2MASS QSO (z=0.15, $L_{bol} = 10^{11} L_\odot$). The spectrum of this source is shown in Figure 3. 2MASS has sufficient sensitivity to measure or put significant limits on a population of intrinsically red QSOs that is suggested to exist by IRAS and radio studies.

References

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Figure 2. Spectra of a selection of extremely late M-dwarfs from Kirkpatrick, Beichman and Skrutskie (1996). The newly discovered 2MASS M10+ dwarf is the coolest known isolated star.

Figure 3. Visual spectrum of the first 2MASS-discovered QSO reported by Cutri *et al.* (1995). This object has z=0.15 and $L_{bol} \sim 10^{11} L_{\odot}$.