Wide-field Infrared Survey Explorer (WISE)

Subsystem Design Specification: WISE Photometry (WPHOT)

DRAFT Version 2.0

March 13, 2009

Prepared by: Ken Marsh & Tom Jarrett

Infrared Processing and Analysis Center
California Institute of Technology

WSDC D-D006

Concurred By:

Roc Cutri, WISE Science Data Center Manager

Tim Conrow, WISE Science Data Center Lead Architect

Ken Marsh, WISE Science Data Center Cognizant Engineer/Scientist

Tom Jarrett, WISE Science Data Center Cognizant Engineer/Science Team Member

Revision History

Date	Version	Author	Description
1/22/08	1.0	K. Marsh/T. Jarrett	Initial Draft
3/28/08	1.1		1st revision
3/13/09	2.0	TJarrett	2nd revision

Contents

List of Figures

1 INTRODUCTION

1.1 Document Scope

This Subsystem Design Specification (SDS) document describes the design of the WISE Photometry module (WPHOT) for the WISE Science Data System (WSDS). The purpose of WPHOT is to characterize the source candidates detected by the MDET module (described in Document WSDC D-004).

1.2 Applicable Documents

This plan conforms to the specifications in the following project documents:

1. WISE Science Data System (WSDS) Functional Requirements Document (WSDC D-R001).
2. WSDS Functional Design Document (WSDC D-D001).
3. MDET Subsystem Design Specification (WSDC D-004).
4. AWAIC Subsystem Design Specification (WSDC D-D005).
5. Software Interface Specification for call to WPHOT.
6. Software Interface Specification for output to source extraction database.

1.3 Requirements

The following requirements (from the WSDC Functional Requirements Document) are relevant related to the design of WPHOT:

L4WSDC-002: The WSDC shall produce a Source Catalog derived from the images used to generate the WISE digital Image Atlas.

L4WSDC-080: The final WISE Source Catalog shall have greater than 99.9% reliability for sources detected in at least one band with SNR>20, where the noise includes flux errors due to zodiacal foreground emission, instrumental effects, source photon statistics, and neighboring sources. This requirement shall not apply to sources that are superimposed on an identified artifact.

L4WSDC-009: The final WISE Source Catalog shall be at least 95% complete for sources detected with SNR>20 in at least one band, where the noise includes flux errors due to zodiacal foreground emission, instrumental effects, source photon statistics, and neighboring sources. This requirement shall not apply to sources that are superimposed on an identified artifact.

L4WSDC-010: The final WISE Source Catalog shall include sources down to SNR=5 in any band, and the completeness and reliability of sources in the Catalog shall be characterized at all flux levels.

L4WSDC-012: Flux measurements in the WISE Source Catalog shall have a SNR of five or more for point sources with fluxes of 0.12, 0.16, 0.65 and 2.6 mJy at 3.3, 4.7, 12 and 23 micrometers, respectively, assuming 8 independent exposures and where the noise flux errors due to zodiacal foreground emission, instrumental effects, source photon statistics, and neighboring sources.

L4WSDC-013: The root mean square error in relative photometric accuracy in the WISE Source Catalog shall be better than 7% in each band for unsaturated point sources with SNR>100, where the noise flux errors due to zodiacal foreground emission, instrumental effects, source photon statistics, and neighboring sources. This requirement shall not apply to sources that superimposed on an identified artifact.

L4WSDC-015: The WISE Source Catalog shall contain the measured in-band fluxes or flux upper-limits in the four WISE bands for objects detected in at least one band in the WISE Atlas Images.

L4WSDC-016: The WISE Source Catalog shall contain uncertainties in the flux measurements (one sigma) in all bands for which a source is detected.

L4WSDC-018: The WISE Source Catalog shall contain uncertainties in the coordinates measurements for each object.

L4WSDC-043: The WSDS Pipeline processing shall detect sources down to a threshold of at least five times the image noise from the calibrated image frames, and the combined Atlas Images.

L4WSDC-044: The WSDS Pipeline processing shall merge source detections in the four WISE bands into a single source catalog entry.

L4WSDC-049: The WSDS Pipeline shall be robust to data missing from one or more bands.

1.4 Acronyms

AWAIC – A Wise Astronomical Image Coadder; the name of the module used to combine a set of focal-plane images to produce an estimate of the intensity distribution on the sky.

co-add – co-added or mosaic images.

FITS – Flexible Image Transport System.

FWHM – Full Width at Half Maximum.

MDET – Multiband DETector; the name of the module whose purpose is to produce a list of candidate source detections.

PSF – Point Spread Function, defined here as the response of a focal plane pixel to a point source, as a function of position on the sky.

SNR – Signal to noise ratio, defined here as the ratio of peak detection signal to the standard deviation of additive noise.

WAPP – Aperture Photometry System (frames)

WAPPco – Aperture Photometry System for the co-add (mosaic) images

WCS – World Coordinate System.

WPHOT – WISE PHOTometry module, described here, which will enable both aperture and profile-fitting photometry based on the list of candidates supplied by MDET.

WPRO – Profile-fitting Photometry System

WSDS – WISE Science Data System.

2 OVERVIEW OF APPROACH

WPHOT is designed to perform the source position and flux characterization step associated with each of the three stages of source extraction during pipeline processing (single-frame, single-epoch 4-band frameset, and final coadd stage). The characterization is based on an input list of source candidate positions produced by MDET using a detection algorithm which makes use of the data at all bands simultaneously.

Since the majority of sources detected by WISE are expected to be spatially unresolved, the optimal approach for source characterization involves profile-fitting photometry (WPRO). Just as with the detection step, this procedure is carried out using the data from all bands simultaneously. The advantages of simultaneous multiband extraction are:

1. Increased sensitivity to weak sources due to the fact that detection is based on the stack of images at all bands.

2. No separate bandmerging step is required, thus avoiding the ambiguities which can occur when trying to associate sources in different bands in the presence of confusion.

3. The higher resolution data at the shorter wavelengths can guide the extraction at the longer wavelengths where the resolution is poorer.

The multiband estimation process represents a departure from the traditional procedure, employed in such software packages as DAOPHOT (Stetson 1987) and SExtractor (Bertin & Arnouts 1996), in which detection and characterization are carried out one band at a time. Another motivation for developing new source extraction algorithms is that currently available packages operate on a single regularly-sampled image rather than a set of dithered images. The procedures employed in MDET and WPHOT are optimized for the latter case.

In addition to profile-fitting photometry, WPHOT includes an aperture photometry system (WAPP) that employs circular apertures to characterize the integrated flux and 'curve-of-growth' of point sources. Both frames and co-adds (mosaics) are measured. Morever, in order to properly characterize the subset of sources which are spatially resolved, we will supplement the profile and aperture-fitting results with basic surface brightness and other morphology metrics using the co-adds, depending on the resources that are available for their development.

1

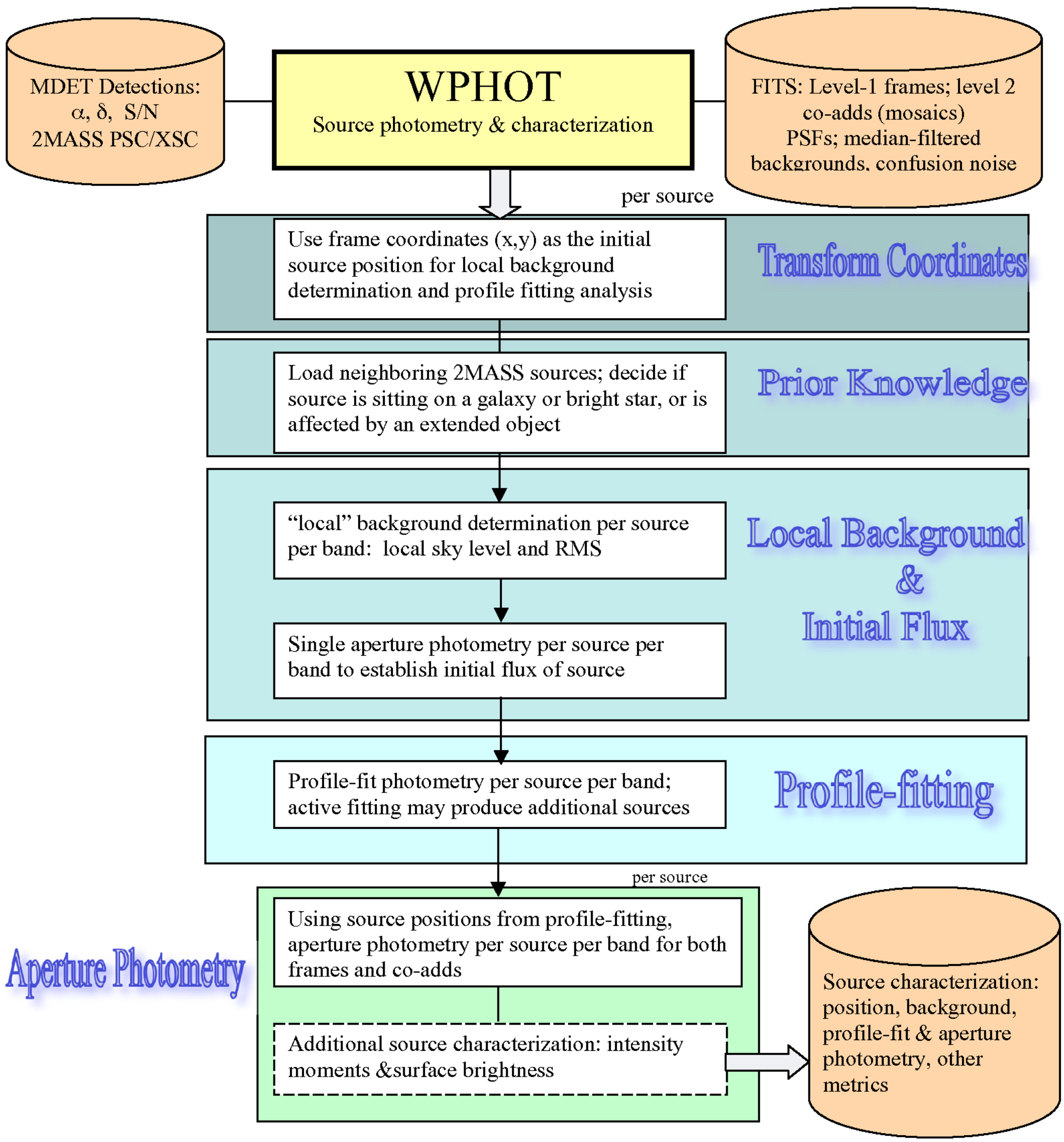


Figure 1: WPHOT flowchart.

2.1 Inputs

1. List of candidate positions generated by MDET (text file).
2. Focal-plane images ("Level 1b frame"); dark-subtracted, flat-fielded, position-calibrated via WCS information in headers (FITS format).
3. PSF and corresponding uncertainty map at each band (FITS format).
4. Additional noise parameters: pixel gain, read noise, flat-fielding error.
5. Coadded image and corresponding uncertainty image at each band (FITS format).
6. Median-filtered background images generated by MDET (FITS format).
7. 2MASS XSC to provide prior knowledge of extended sources.
8. 2MASS PSC to provide prior knowledge of very bright stars

2.2 Outputs

The output consists of a single file in text format, one line per source, containing the following information:

1. Sequential number of source; the ordering is nominally in decreasing SNR.
2. Profile-fit results: RA [deg] & Dec [deg] of the source, the estimated flux [dn] at each of the four bands, and the corresponding uncertainties in each of those six quantities.
3. Reduced chi squared value for the overall fit and for the individual bands.
4. Number of components in the fitted blend, plus a flag which indicates if this source was added via active deblending.
5. Number of components in the fitted blend, plus a flag which indicates if this source was added via active deblending.
6. Aperture photometry results: Source centroid positions and aperture fluxes in a series of apertures centered on the profile-fitted position, in each of the four bands; the corresponding uncertainties in each of those quantities. Additional source characterization measurements, including surface brightness, size and shape.

3 TECHNICAL DESCRIPTION

The data processing steps involved in the source characterization procedure are illustrated in Figure 1. They include:

1. Subtract slowly-varying background from each frame using the sky background estimated via median filtering in MDET. This serves as a pre-flattening step which increases the accuracy of subsequent sky background estimation in annuli surrounding the sources.

2. Do profile-fitting photometry for all of the candidate sources in detection list from MDET, subtracting the estimated contributions from the focal-plane images after each extraction.

3. Do aperture photometry for all of the candidate sources using the original (unsubtracted) focal-plane images, placing the apertures at the locations found during the profile-fitting photometry step. Additional aperture measurements are made on the co-adds.

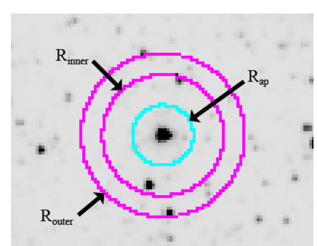
3.0.1 Coordinate Transformation

MDET utilizes the level-2 coadded frames to detect sources. The coordinate positions are recorded in the WCS system (equatorial). WPHOT uses level-1 frames to measure fluxes, and as such, requires the detection positions to be in frame coordinates (x,y). The purpose of this routine is to transform the equatorial coordinates into frame coordinates.

3.0.2 Local Background

The sky background is composed of real astrophysical diffuse signal (e.g., infrared cirrus, zodiacal emission), faint stars (fluctuating at the noise level), and diffuse artifacts (e.g., scattered light, diffraction spikes and latent ghosts). These background components have size scales that range from point-like to infinitely extended (e.g., zodiacal light). What is important with aperture photometry of point sources is the "local" background value.

The local background is determined from the pixel value distribution within a circular annulus centered on the sourc MDET position. The pixel value distribution must be first trimmed (masked) of extrema to arrive at a representative estimate of the background plus noise fluctuations and its uncertainty. The most accurate method is to compute the mean of the distribution after n-sigma trimming; however, the demands of the survey require a more robust (even if noisier) estimate that is resistent to cosmic rays and/or rogue pixels, notably the median of the trimmed pixel distribution. With this method, we will compute the median average, b_λ, representing the local "sky" background level. Instead of the standard median calculation of sample – sorting and taking the mid-point - -we will construct a histogram of the distribution and derive the 50%-tile, representing the median of the histogram. This alternative method (histogram vs. sorting) is much faster, roughly a factor of 3 in computation speed. The histogram bin width is set by the standard deviation in the background pixel distribution, or the sigma of the population.



The background error, or sigma in the mean, is derived from the the error propogation that follows the instrument characteristics and the noise model that is tracked by AWAIC and passed to on to WPHOT. With this noise model, the uncertainty in the background sky level is

$$\sigma_b^2 = \frac{F_b}{N_b^2} \sum_{i=1}^{N_b} (\sigma_i^2) \tag{1}$$

where N_b is the number of pixels in the annulus and σ_i is the measurement uncertainty for detector/frame pixel i, and F_b is the correlation factor that is appropriate to the images being measured (for WISE frames, the factor is unity, and for co-adds it ranges between 30 and 225, W1 to W4, respectively).

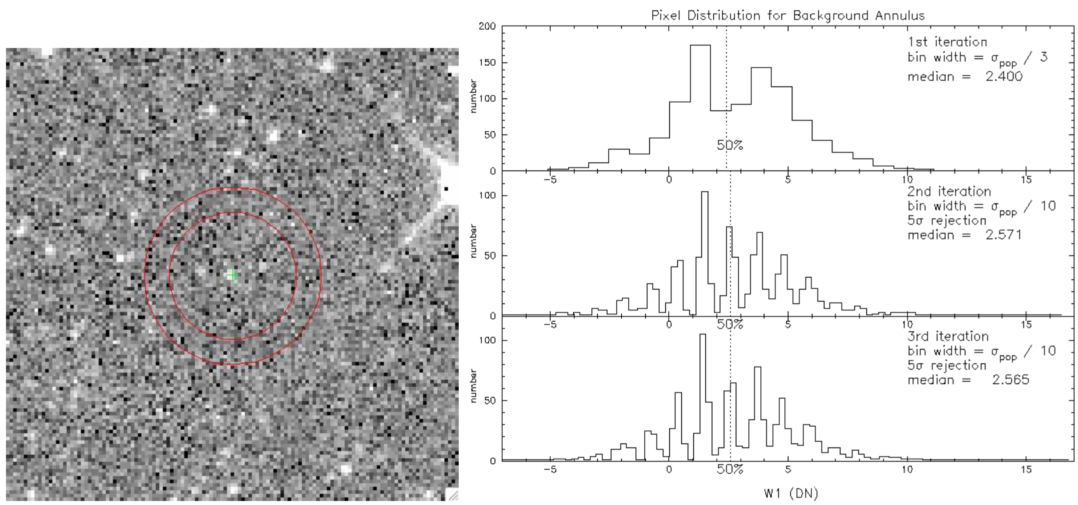


Figure 2: Example of a background annulus and it's pixel value distribution. The histograms show three iterations of extrema trimming.

Size Considerations

Choosing the optimal size for the annulus is an important consideration toward accurate photometry. The annulus must be large enough to avoid the influence of the point spread function and to minimize the Poisson component of the sky pixels (see equation below). On the other, it must also be small enough to represent the "local" sky value (that is to say, the fluctuations that are present in the aperture should be of similar amplitude in the annulus).

Moreover, in order to accomodate the possibility of the source being fuzzy galaxy, the annulus should extend beyond the size expected for most galaxies in the sky; see APPENDIX discussion of extended sources. Since the annulus may be large enough to experience gradients in the background, we first subtract the frame images with the median-filtered background (determined by MDET); this effectively flattens the backgrounds on size scales that are set by the median filtering. With this step, the sky determined from the local annulus should reflect the "local" background for the source in question.

2MASS and Spitzer-IRAC Aperture Geometry

Let us first consider what was done with 2MASS. For standard 2MASS point source photometry, the annulus that was used: R$_{inner}$ = 14″, R$_{outer}$ = 20″, with 2″ pixels that translates to 160 pixels in the annulus. The 2MASS beam is about 2.5″, so R$_{inner}$ is $\sim 6\times$ FWHM. For the combined calibration fields, 2MASS used a larger annulus, $24 - 30''$ in size, or roughly $\sim 10\times$ FWHM. The standard calibration aperture for IRAC is 12″, and the annulus is $14.4 - 20''$, which compared to the 2″ beam is $\sim 7 - 10\times$ FWHM.

The WISE Annulus

For WISE, the FWHM=6$''$ for the short channels, and so using 2MASS/IRAC as a guide, the inner radius would be $\sim 40-50''$ (and $\sim 80-100''$ for WISE-4); with 2.75$''$ pixels, that translates to R$_{inner} \sim 15-18$ pixels. For the width, using a similar area as the 2MASS/IRAC annulus, then R$_{outer} \sim 19$ pixels. Since that is a relatively thin aperture, subject to pixelization effects, it would be better to extend it to a width of 4 - 5 pixels, or R$_{outer} = 20$ - 22. Consequently, the proposed annulus for WISE point sources is: 15 to 22 pixels for WISE-1,2,3,4

The current (as of Mar 13, 2009) annulus settings are: $50-70''$ (for all four bands), corresponding to 18-25 pixel radius in W1, W2, W3, and 9 to 13 pixels for W4. This setting is constrained by the W4 beam.

3.1 Profile fitting photometry (WPRO)

The purpose of this step is to make a maximum likelihood estimate of the source position and the set of fluxes at the four wavelengths for each source candidate identified by the detection module MDET. The candidate source and its neighbors (i.e., adjacent candidates whose PSF responses overlap significantly with the primary candidate) are grouped into blends, and their parameters estimated simultaneously. This procedure is referred to as *passive deblending*.

3.1.1 Procedure

Profile-fitting photometry is based on the following measurement model for a blend consisting of $N_{\rm B}$ components:

$$\rho_{\lambda i} = \sum_{n=1}^{N_{\rm B}} (f_\lambda)_n H_\lambda(\mathbf{r}_{\lambda i} - \mathbf{s}_n) + b_\lambda + \nu_{\lambda i} \tag{2}$$

where $\rho_{\lambda i}$ is the observed value of the ith pixel at 2-d sky location $\mathbf{r}_{\lambda i}$ in the waveband denoted by subscript λ, $\mathbf{s}_n$ is a 2-d vector representing the location of the nth blend component, $(f_\lambda)_n$ is the flux in the λth waveband, $H_\lambda(\mathbf{r})$ is the PSF, $b_{\lambda i}$ is the local background, estimated in an annulus surrounding the candidate position, and $\nu_{\lambda i}$ is the noise, assumed to be a spatially and spectrally uncorrelated zero-mean Gaussian random process with variance $\sigma^2_{\lambda i}$. The latter quantity includes the various noise components in the error model and may be expressed as:

$$\sigma^2_{\lambda i} = (\rho_{\lambda i} - b_\lambda)/g_\lambda + [(\rho_{\lambda i} - b_\lambda)(\sigma_{\rm ff})_\lambda]^2 + (N_{\rm R})^2_\lambda + (\sigma_b)^2_\lambda + [(f_{\rm ap})_\lambda \delta H_\lambda(\mathbf{r}_{\lambda i} - \mathbf{s}_n)]^2 \tag{3}$$

where g_λ, $(\sigma_{\rm ff})_\lambda$, $(N_{\rm R})_\lambda$ and $(\sigma_b)_\lambda$ represent the pixel gain [counts/dn], flat-fielding error, read noise and standard deviation of the local background, respectively, and $\delta H_\lambda(\mathbf{r})$ represents the PSF uncertainty which must be scaled by the source flux; we use a preliminary estimate of the aperture flux, denoted by $(f_{\rm ap})_\lambda$.

The set of unknowns in the estimation process can be represented by an $n_{\rm p}$-dimensional parameter vector, $\mathbf{z}$, defined as:

$$\mathbf{z} \equiv [\{\mathbf{s}_n, \{(f_\lambda)_n : \lambda = 1, \ldots N_\lambda\} : n = 1, \ldots N_{\rm B}\}] \tag{4}$$

where N_λ represents the number of wavebands, and the number of unknowns is given by $n_{\rm p} = N_{\rm B}(N_\lambda + 2)$.

The solution procedure is to maximize the conditional probability $P(\rho|\mathbf{z}, N_{\rm B})$ with respect to $\mathbf{z}$, where:

$$\ln P(\rho|\mathbf{z}, N_{\rm B}) = -\frac{1}{2}\sum_\lambda \sum_i \frac{1}{\sigma^2_{\lambda i}}[\rho_{\lambda i} - b_\lambda - \sum_{n=1}^{N_{\rm B}} (f_\lambda)_n H_\lambda(\mathbf{r}_{\lambda i} - \mathbf{s}_n)]^2 + \text{const.} \tag{5}$$

in which the summation over i is for all pixels within some predefined "fitting radius", $r_{\rm fit}$, of the candidate source location.

The quality of the fit can be evaluated using the reduced chi squared, given by:

$$\chi^2_\nu = \frac{1}{N_{\rm obs} - n_{\rm p}} \sum_\lambda \sum_i \frac{1}{\sigma^2_{\lambda i}} [\rho_{\lambda i} - b_\lambda - \sum_{n=1}^{N_{\rm B}} (\hat{f}_\lambda)_n H_\lambda(\mathbf{r}_{\lambda i} - \hat{\mathbf{s}}_n)]^2 \tag{6}$$

where $N_{\rm obs}$ represents the total number of pixel values used in the solution, and $(\hat{f}_\lambda)_n$ & $\hat{\mathbf{s}}_n$ represent the estimated values of the respective quantities.

If $\chi^2_\nu \sim 1$, the fit is regarded as satisfactory. However if χ^2_ν is larger than some critical value, $(\chi^2_\nu)_{\rm crit}$, or if the reduced chi squared for an individual band (denoted $(\chi^2_\nu)_\lambda$) exceeds a related threshold, $(\chi^2_\nu)'_{\rm crit} = 1 + [(\chi^2_\nu)_{\rm crit} - 1]/\sqrt{\phi}$ (where ϕ is the relative number of degrees of freedom of the single-band fit with respect to the multiband fit), then we consider that the source model has not satisfactorily reproduced the observed data. We then examine the hypothesis that the true intensity distribution involves additional point source components. In this procedure, referred to as *active deblending*, we successively add more source components (thereby increasing $N_{\rm B}$) until either $\chi^2_\nu \leq (\chi^2_\nu)_{\rm crit}$ or else the blend number reaches some predefined limit, $(N_{\rm B})_{\rm max}$, at which point we conclude that a model consisting of a few point sources is not consistent with the observations.

At each iteration of the active deblending procedure, the mechanism for adding a new source component is as follows:

1. Construct a source model consisting of $N_{\rm B}$ components in the locations estimated in the current solution, plus an additional component offset by $(\Delta x, \Delta y)$ from the primary source.

2. At each location on a regularly-sampled grid of $(\Delta x, \Delta y)$ in a rectangular region surrounding the primary source, obtain the maximum likelihood solution for the set of $(N_{\rm B} + 1)$ fluxes of this set of components.

3. Calculate the corresponding χ^2_ν as a function of $(\Delta x, \Delta y)$.

4. Find the minimum of χ^2_ν; we now have a set of $(N_{\rm B} + 1)$ component locations which serve as a starting model for a full maximum likelihood solution (position and fluxes).

At this point, two tests are performed to determine whether the new solution (involving the extra component) is warranted by the data:

1. Chi squared test (overall and for individual bands) as above. This test determines whether the data (and single-band subsets of the data) are consistent with the model.

2. Require that the overall reduced chi squared decrease by at least a minimum amount, i.e. $\Delta\chi^2_\nu \geq (\Delta\chi^2_\nu)_{\rm min}$. The difference in chi squared corresponds to a likelihood ratio, and thus indicates the extent to which a model with $(N_{\rm B} + 1)$ components is more likely than a model with $N_{\rm B}$ components.

During this active deblending procedure, any source candidates that were missed in the multiband detection (MDET) step due to cross-band blending will be recovered, since these sources will produce large values of $(\chi^2_\nu)_\lambda$ in the band (or bands) in which they have significant strength.

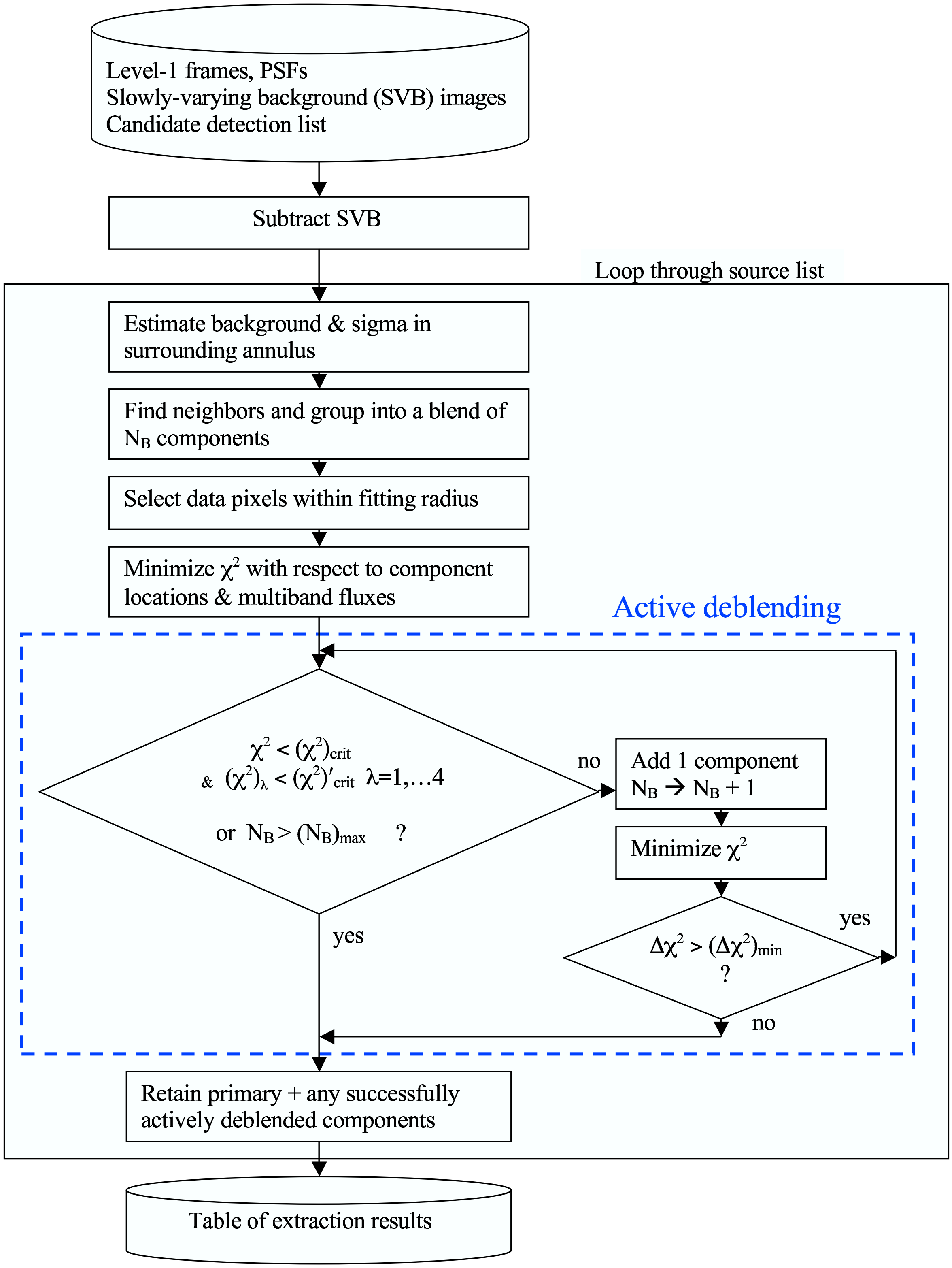


Figure 3: WPRO flowchart.

The overall profile-fitting photometry procedure is illustrated by the flowchart in Figure 2; the active deblending procedure is contained within the blue dashed rectangular box.

When a satisfactory solution has been obtained, the uncertainties in the estimated parameters (position and fluxes) are obtained using:

$$\sigma(z_j)^2 = (\gamma^{-1})_{jj} \tag{7}$$

$$\text{where} \quad \gamma \equiv -E\frac{\partial}{\partial \mathbf{z}}\frac{\partial^{\mathrm{T}}}{\partial \mathbf{z}} \ln P(\rho|\mathbf{z}, N_{\mathrm{B}}) \tag{8}$$

in which E is the expectation operator and T denotes transpose.

The way in which the above estimation procedure is implemented is that we start with the brightest source in the candidate list and estimate its parameters as above. We then proceed as follows:

1. Write out the source position and multiband fluxes associated with the candidate itself and with any actively-deblended source components (each of which is regarded as a separate source.

2. Discard the results for any "passively-deblended" components, i.e., those components corresponding to neighboring candidates in the MDET detection list—these candidates will be processed later.

3. Subtract the estimated contributions of the primary source (+ actively-deblended components) from the focal-plane images.

We then repeat the procedure for the next brightest candidate, and so on until the MDET candidate list is exhausted.

3.1.2 The Point Spread Function

PSFs for WISE profile-fitting photometry will be based on observations of bright stars, with some guidance from theoretical or laboratory-measured PSFs. Since the PSF shape, $H_\lambda(\mathbf{r})$, is expected to vary significantly over the focal plane due to distortion from the telescope optics, allowance must be made for this effect in the profile-fitting photometry procedure described above. A practical way of handling the nonisoplanicity is to use a library of PSFs corresponding to a grid of locations on the focal plane, and then select the appropriate PSF for a given focal-plane location using interpolation or table lookup.

Each PSF in the library represents an average over a subregion ("segment") of width W_{P}, over which we approximate the PSF as locally isoplanatic. The segment must, of course, contain a sufficient number of stars to provide an accurate PSF estimate and meaningful statistics on shape variation. However, the fundamental constraint on W_{P} is driven by the fact that the photometric accuracy on bright stars must meet Functional Requirement L4WSDC-013, which dictates a relative photometric flux accuracy of 7% or better for an unsaturated source with SNR > 100. This, in turn, leads to a maximum acceptable value of W_{P} above which the nonisoplanicity of the PSF over the segment would result in unacceptably large PSF errors. Quantitatively, the selection of an appropriate W_{P} on this basis must await upcoming laboratory measurements and theoretical PSF calculations which will provide information on PSF shape variation at a substantial number of points over the focal plane.

PSF generation

For the particular band, we assume that there are N bright star images which fall within the focal-plane segment under consideration. Let $\zeta(\mathbf{r}'_j)$ represent the jth sample of the nth star image after background subtraction and interpolation onto a suitably fine grid $\{\mathbf{r}'_j\}$ (a sampling interval of half a focal plane pixel should suffice); we will use primed coordinates to represent locations on the PSF representation grid in order to distinguish them from focal-plane pixel locations. We assume that the original focal plane pixels provide approximately (or better than) Nyquist sampling.

The measurement model for the PSF is then:

$$\zeta_n(\mathbf{r}'_j) = f_n H(\mathbf{r}'_j - \mathbf{s}_n) + \nu_{nj} \tag{9}$$

where $\mathbf{s}_n$ is the location of the nth star in the segment. The origin of the coordinate system for the PSF image is defined to be at the star location.

The noise, ν_{ni}, is assumed to be an uncorrelated Gaussian random process for which

$$\sigma_{nj}^2 \equiv E\,\nu_{nj}^2 = \zeta_n(\mathbf{r}'_j)/g + \sigma_b^2 + N_{\mathrm{R}}^2 \tag{10}$$

From the set of star images, we can make a maximum likelihood estimate of the PSF using:

$$\hat{H}(\mathbf{r}'_j) = \frac{\sum_{n=1}^{N} \hat{f}_n \zeta(\mathbf{r}'_j + \hat{\mathbf{s}}_n)/\sigma_{nj}^2}{\sum_{n=1}^{N} \hat{f}_n^{\,2}/\sigma_{nj}^2} \tag{11}$$

where $\hat{f}_n$ and $\hat{\mathbf{s}}_n$ represent estimates of the flux and position, respectively, of the nth star. For bright stars, an accurate value for $\hat{f}_n$ can be obtained via aperture photometry.

The source position $\hat{\mathbf{s}}_n$ can be estimated by adjusting the positional offset of the star image for maximum correlation with respect to an *a priori* PSF, $H_0(\mathbf{r}')$, obtained theoretically based on a knowledge of the optical system, or by laboratory measurement. This is accomplished by numerical minimization, with respect to $\mathbf{s}_n$, of:

$$\phi(\mathbf{s}_n) = \sum_i [\zeta_n(\mathbf{r}'_j) - \hat{f}_n H_0(\mathbf{r}' - \mathbf{s}_n)]^2/\sigma_{ni}^2 \tag{12}$$

Estimating the PSF uncertainty

The PSF uncertainty, $\delta H(\mathbf{r})$, which enters into the photometry noise model, can be estimated by examining the behavior of the data residuals after subtracting a point source model. The ith data residual from the nth star is given by:

$$\Delta_{ni} = \rho_{ni} - \hat{f}_n H(\mathbf{r}_i - \hat{\mathbf{s}}_n) \tag{13}$$

We model Δ_{ni} as a zero-mean Gaussian random process with variance

$$\mu_{ni}^2 = \rho_{ni}/g + \sigma_{\mathrm{b}}^2 + N_{\mathrm{R}}^2 + \hat{f}_n^{\,2} \delta H(\mathbf{r}_i - \hat{\mathbf{s}}_n)^2 \tag{14}$$

where $\delta H(\mathbf{r})$ represents the PSF uncertainty at offset $\mathbf{r}$ from the PSF origin.

Suppose that the position $(\mathbf{r}_i - \hat{\mathbf{s}}_n)$ falls within the jth pixel on the grid used to represent the PSF, i.e.,

$$x'_j - \frac{\delta x}{2} \;<\; x_i - \hat{\xi}_n \;\le\; x'_j + \frac{\delta x}{2} \tag{15}$$

and

$$y'_j - \frac{\delta y}{2} \;<\; y_i - \hat{\eta}_n \;\le\; y'_j + \frac{\delta y}{2} \tag{16}$$

where (x'_j, y'_j) represent the components of $\mathbf{r}'_j$, $(\hat{\xi}_n, \hat{\eta}_n)$ represent the components of $\hat{\mathbf{s}}_n$, and $\delta x, \delta y$ represent the sampling intervals of the PSF grid in the x and y directions, respectively.

Then:

$$\mu_{ni}^2 = \sigma_{ni}^2 + \hat{f}_n^{\,2} \delta H_j^2 \tag{17}$$

where $\delta H_j \equiv \delta H(\mathbf{r}'_j)$ and

$$\sigma_{ni}^2 = \rho_{ni}/g + \sigma_{\mathrm{B}}^2 + N_{\mathrm{R}}^2 \tag{18}$$

Thus the probability density of the set of local data residuals, Δ, conditioned on δH_j, is given by:

$$\ln P(\Delta|\delta H_j) = -\frac{1}{2}\sum_{n,i} \frac{\Delta_{ni}^2}{\sigma_{ni}^2 + \hat{f}_n^{\,2}\delta H_j^2} - \frac{1}{2}\sum_{ni} \ln(\sigma_{ni}^2 + \hat{f}_n^{\,2}\delta H_j^2) + \text{const.} \tag{19}$$

where the summations are over all n, i which satisfy (15) and (16) for a given j.

This expression is maximized when:

$$\delta H_j^2 = \frac{\sum_{n,i} w_{nij}(\Delta_{ni}^2 - \sigma_{ni}^2)/\hat{f}_n^{\,2}}{\sum_{n,i} w_{nij}} \tag{20}$$

where:

$$w_{nij} = \frac{1}{(\sigma_{ni}^2/\hat{f}_n^{\,2} + \delta H_j^2)^2} \tag{21}$$

Since δH_j is present on both sides of (20), iterative solution is required. Convergence is rapid, however, and one or two iterations should suffice.

Steps involved in PSF generation

For each focal plane segment:

1. Locate all stars above a given flux threshold for the particular band.
2. Estimate PSF and its uncertainty using (11) and (20).
3. For each individual star, examine the quality of its profile fit by evaluating χ_ν^2 using (6).
4. List any stars for which χ_ν^2 exceeds a predefined threshold (~ 2); discard the star with the highest χ_ν^2.
5. Iterate from step 2 until all all remaining stars used in the PSF estimation have acceptable profile fits.

PSF selection

To do photometry, we need to know the PSF and its uncertainty at a continuous set of locations over the focal plane rather than at the coarse grid of locations corresponding to our PSF library. Although we could, in principle, accomplish this by interpolating between adjacent library PSFs, the interpolated PSF would, in general, have a larger variance than the library PSFs, depending on the degree of correlation between them. This limitation could be overcome by making the grid of PSFs sufficiently fine that adjacent PSFs are highly correlated; such a grid could be obtained without reducing the number of PSF estimation stars per segment by spacing the PSFs by an interval smaller than the width, W_{P}, of a segment. Since neighboring PSF estimates would then involve some of the same stars, there will be correlation between these estimates and hence continuity of PSF shape (and its uncertainty) over the focal plane. Simple table lookup could then be used to select the appropriate PSF for a given place on the focal plane.

3.2 Aperture photometry (WAPP)

Introduction

The WAPP system performs multi-aperture photometry and source characterization, which is carried out after the profile-fitting system (WPRO) has completed; see Figure 1. The WPRO extraction list is used as the input source list for WAPP. In this way every source extracted by WPRO using both passive and active deblending will have an aperture flux. Measurements are carried out for both frames and co-adds.

Fixed aperture photometry serves several purposes, including

- source flux estimation in support of profile-fitting photometry,
- construction of curve-of-growth data for aperture corrections,
- more accurate flux determination for very bright sources,
- serve as a truth measurement to test the robustness of profile-fitting photometry, and
- accurate source flux determination for extended sources in which the PSF does not accurately model the light distribution.

There are three main parts to the WAPP system: aperture photometry using the frames, aperture photometry using the co-adds and additional source characterization using the co-adds. The system is described below.

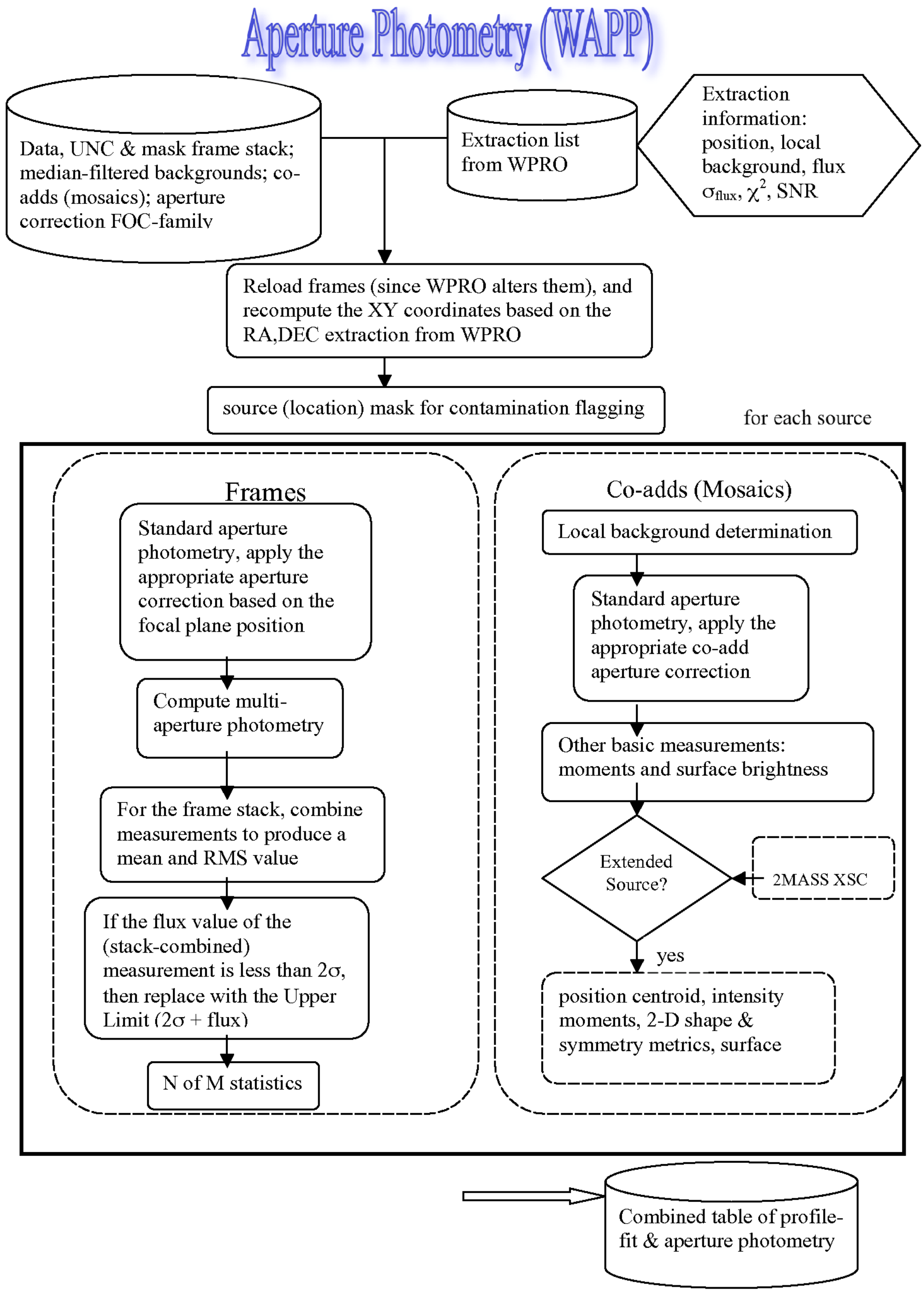


Figure 4: WAPP flowchart.

3.2.1 Special Inputs

Aperture photometry and source characterization is carried out using Level-1 frame images and co-adds. Both the frames, co-adds and their associated uncertainties and masks are inputs to WPHOT. Either single or multi-band frames will be supported.

The detection list is provided by the profile-fitting system, which has used MDET for its preliminary detection list. The source detections include profile-fit determinations of the positions, flux and its uncertainty, and the reliability of the fit. Finally, each source has an associated local background and uncertainty that is determined by WPHOT before profile fitting is carried out.

Information regarding nearby extended sources (e.g., large galaxies) is provided by the 2MASS XSC, and very bright stars by the 2MASS PSC. The input parameter list provides information that WAPP requires to run, including the frame information (e.g., gain, read noise, pixel scale), local background annulus size, aperture sizes and flux calibration information

3.2.2 Processing Overview

The primary function of WAPP is to carry out circular aperture photometry, and the secondary function is to conduct source characterization. It uses the local background per source per band determined in the pre-WPRO processing (which is based on MDET positions).

Aperture measurements are made for all of the WPRO detections (that is first run in WPHOT), placing the center of the nested apertures on the refined WPRO positions. The aperture MASK is scanned for bad or fatal-flagged pixels, and the aperture flux is flagged accordingly. If nearby stars are detected within the aperture, the flag is set to indicate “contamination”. If the source is suspected to be extended (e.g., poor χ^2 value), then further characterization measurements are carried out; discussed below. The processing flow is depicted in the Aperture Photometry Flowchart

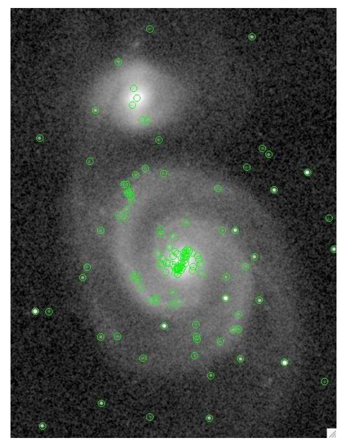


Figure 5: M51 2MASS point sources

3.2.3 Prior Knowledge using 2MASS

Point sources are sometimes superimposed on extended sources (e.g., very bright stars or large galaxies) and their flux measurement can be biased by the surrounding/nearby extended emission. Conversely, point-like sources can be spuriously detected on large, extended objects. See the discussion in APPENDIX “Extended Sources and Advanced Characterization.” Figure 4 shows the nearby galaxy M51ab with 2MASS point source detections overlayed. Many of these sources are pieces of the galaxy (e.g., SF/HII regions) or noise bumps that are enhanced by the underlying galaxy light. Without even minimal characterization of the extended source, we have no way of reliably flagging “point” sources that might be contaminated or modified by the underlying emission. At the very least the 2MASS XSC will be used as a “prior” list of extended sources (i.e., galaxies) in the local region. The XSC gives both the location and size/shape of the galaxy, and therefore can be used to alert WPHOT to its presence. Based on the K-band size and shape parameters, it is relatively straight forward to estimate or predict the corresponding WISE-W1/W2 parameters. For the longer wavelengths the disconnect between the near-infrared to the mid-infrared becomes large enough that we can only rely upon the prior K-band information to predict the W1 or W2 emission.

This knowledge could be used with the following logic:

- If the source is located with Rmingal pixels of a known galaxy, then assume the source is the center of the galaxy and treat accordingly (e.g., do not attempt to deblend; characterize assuming extended emission).
- If the source lies within the galaxy' sphere of influence (Rsizegal), then assume the source is affected by the galaxy and treat accordingly (e.g., do not assume it is extended, but is part of the galaxy itself).
- If the source lies with with scale factor of the galaxy size (Rsizegal * X), then flag the source as potentially being affected by the galaxy (whether true or not, this flag simply states that there is a big galaxy nearby).
- If the source lies within some radius of a very bright star, then flag the source as potentially corrupted by bright-star artifacts (e.g., diffraction spikes). If the source lies on top of a known very bright star, then treat accordingly (e.g., attempt deblend?). See the example of a very bright star (Beta Pegasus) as seen with 2MASS

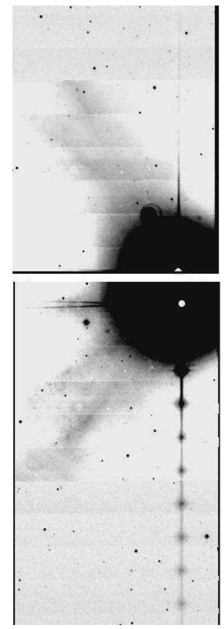


Figure 6: β Peg

Note: none of these criteria are part of the Version 2 WPHOT. Their implementation into Version 3 is TBD.

3.2.4 Masked and bad pixels

The WISE frame arrays will be laced with flagged "bad" pixels. It is not practical to replace or recover those bad pixels in the frames. Instead, however, the co-add measurements will be robust (to bad pixels) and should be the best aperture measurement accordingly. Hence, the frame measurements can have bad pixels in their flux sum (with the flag set accordingly) and thus their integrated flux is suspect., whereas the co-added integrated flux should be satisfactory. For aperture corrections (i.e., curve of growth) using the standard aperture, sources with masked pixels should be rejected outright.

Summary of flagged or masked pixel processing:

- For the standard aperture measurements, do not attempt bad pixel or masked source recovery; instead, the measurement is flagged as 'bad'.
- Co-add measurements will not be subject to bad or fatal pixes (assuming typical coverage) and thus will have satisfactory integrated fluxes.

3.2.5 Circular Apertures

Multiple aperture photometry is the primary function of the WAPP system. A set of nested circular apertures centered on the source (as determined by WPRO) provides the "curve of growth" for a source. The aperture sizes range from the smallest APMIN (two or three pixels, TBD) to the largest APMAX which is constrained by the background annulus. The photometry is carried out using code, developed by 2MASS, that is adapted for WISE images. It includes fractional pixel computations and the ability to use non-circular (elliptical) apertures that may be deployed in future version of WAPP.

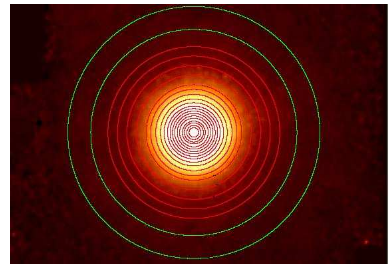


Figure 7: Circular apertures centered on NGC6703

Formal frame measurements:

$$aperture\ area,\ N_{ap} = \pi \times R_{ap}^2 \tag{22}$$

$$integrated\ flux,\ (F_{ap})_\lambda = \sum_{i=1}^{N_{ap}}((f_\lambda)_i - b_\lambda) \tag{23}$$

$$flux\ uncertainty,\ \sigma_{bann}\ (Eq.1),\ (\sigma_{ap}^2)_\lambda = \frac{(F_{ap})_\lambda}{G} + (N_{pix}(\sigma_{bann}^2)_\lambda) + (\sigma_{ann}^2)_\lambda \tag{24}$$

$$flux\ uncertainty,\ combined\ Eq.1\ \&\ Eq.2,\ (\sigma_{ap}^2)_\lambda = F_a \sum_{j=1}^{N_{pix}}(\sigma_j^2)_\lambda + \frac{F_b\ N_{pix}^2}{N_b^2}\sum_{i=1}^{N_b}(\sigma_i^2)_\lambda \tag{25}$$

where G is the gain (electrons per DN), N_{ap} is the number of pixels in the circular aperture of radius R_{ap}, N_b is the number of pixels in the background annulus, b_λ and $(\sigma_{bann})_\lambda$ are the source-trimmed median sky background level and RMS in the annulus pixel distribution, respectively, $(\sigma_{ann})_\lambda$ is the uncertainty due to the finite annulus (see Eq. 1), and $(\sigma_b)_\lambda$ is the measurement uncertainty detector/frame pixel based on the error model (see Eq. 2), F_a and F_b are the pixel correlation factors, where they are roughly equal to each other (see Eq. 2 for more details)..

3.2.6 Combining Flux Measurements for Frames

Multiple frame measurements require optimal combination of the individual frame measurements. The combination is carried out using a weighting scheme that is based on the inverse variance of the measurement.

$$weighted\ mean\ \bar{f} = \sum_{i=1}^{N}\frac{f_i \times w_i}{w_t} \tag{26}$$

$$weights\ w_i = {\sigma_i}^{-2} \tag{27}$$

$$summed\ weights\ w_t = \sum_{i=1}^{N} w_i \tag{28}$$

$$variance\ of\ the\ weighted\ mean\ \sigma_{\bar{f}}^2 = \sum_{i=1}^{N}\frac{1}{{w_i}^2} \tag{29}$$

$$biased\ weighted\ sample\ variance\ \sigma_{weighted}^2 = \sum_{i=1}^{N}\frac{w_i(f_i - \bar{f})^2}{w_t} \tag{30}$$

$$
\begin{aligned}
\textit{unbiased weighted sample variance } s^2 &= \frac{w_t}{(w_t{}^2 - \sum_{i=1}^{N} w_i{}^2)} \sum_{i=1}^{N} w_i (f_i - \bar{f})^2 && (31)\\
\textit{standard error of the mean } s_{\bar{f}} &= \frac{s}{\sqrt{N}} && (32)\\
\textit{flux } \chi^2 &= \frac{1}{N} \sum_{i=1}^{N} \frac{(f_i - \bar{f})^2}{\sigma_i^2} && (33)
\end{aligned}
$$

where $\bar{f}$ is the weighted mean flux, N is the number of measurements, f_i is the flux of the ith measurement, w_i is the weight of the ith element, w_t is the sum of the weights.

To summarize, for a set of N measurements, the inverse variance-weighted mean ($\bar{f}$) represents the optimally combined flux, while the unbiased weighted sample variance (s^2) represents the scatter in the measurements, and the standard error of the mean (s) represents the precision of the combined flux value. If the error model is correct, then the variance of the weighted mean ($\sigma_{\bar{f}}^2$) should closely approximate the square of the standard error of the mean.

4 Schedule

- Peer Review (March, 2008)
- v0 2/27/08 prototype (single frame, multi-band), data flow testing – Input frames, masks & detection lists – Local backgrounds (stats) – Aperture photometry – Preliminary output table
- v1 6/19/08 payload ground testing; prototype multi-frame – Profile-fitting (active and passive deblending, isoplanatic PSF) – Other source Characterization – Full output table
- V2 2/28/09 Nonisoplanicity capability in WPRO, PSF generation software – Input median-filtered background images – Coadded aperture photometry (prototype multi-frame)
- V3 8/4/09 Pre-launch version: Complete functionality, PSF set, optimized parameters
- V3.5 12/30/09 Post-launch tuneup of parameters/code
- V4 9/20/09 Version for final processing; PSFs derived from all available data

5 Issues and Outstanding Work to be Completed

Note: this section is now out of date, but is included for historical reasons.

- PSF generation
- Focal Plane-dependent PSFs ??
- Focal Plane-dependent curve-of-growth measurements ?
- Parameter tuning
- Driving thresholds for active deblending
- Coadd measurements
- Upper limits
- Masked/bad-pixel recovery
- Extended sources (no plan to properly deal with)
- Very bright stars & saturated stars

Parameters to determine:

- Set of circular apertures
- Minimum aperture size
- Maximum aperture size

- Annulus geometry
- Bad pixel replacement criteria
- Prior knowledge of galaxies and bright stars
- χ^2 limit to test for extended emission

Local Background Annulus:

- Issue: Minimum/Maximum annulus size?
- Issue: Do we use the same annulus for all four WISE bands, based on WISE-4 ?

What do do about flagged or bad pixels:

- Issue: How close to the central position do we attempt to rectify bad pixels?
- Issue: Do we use the PSF or a gaussian model to compute the maximum likelihood value?
- Issue: What about bad pixels in the annulus?
- Issue: When do we correct for bad pixels? Do we correct for bad pixels in the annulus?

Coadded Frames

- Where do we incorporate coadded frames into WAPP?
- How do we join frame and coadded results into a merged table?

Extended Sources

- Primary– Do we attempt to identify extended sources and (potentially) improve the point source photometry that is affected/contaminated by the extended emission?
- Secondary– Do we produce (and validate) images that have calibrated diffuse/extended emission? That is to say, is every pixel, whether it filled with Zody, or cirrus, or a piece of a galaxy have a calibrated surface brightness?.
- Secondary–Do we attempt to detect and characterize discrete extended sources (e.g., galaxies) ? Do we add these measurements into the WISE source catalog(s) ?
- Issue: What level of characterization do we carry out? (note that there is no budget or charge from the science team to work on extended sources)
- Issue: Bright stars – Any special processing that is needed?

6 TEST PLAN Description

Note: this section is now out of date, but is included for historical reasons.
Data Sets

- WISE image simulations
- Spitzer NEP/SEP mini-surveys
- Spitzer GLIMPSE/MIPSGAL/SWIRE
- 2MASS+IRAC M67

General list of items to test WPHOT:

- Integrity & robustness of the algorithms
- Reliability (χ^2 metric; active deblending; N out of M)
- Completeness in confused instances (WPRO)
- Memory management for deep coverages
- Speed management (active deblending thresholding)

WAPP Annulus/Aperture testing

- Local background statistics; pixel-value histogram statistics.
- Small apertures, to test that the fractional-pixel algorithm is working as designed.
- Large apertures, to test the integrity of the system.
- Full range in fluxes, from noise to bright-saturated stars.

WAPP functionality testing

- Source subtraction
- Intensity moments
- Size and shape measurements
- Surface brightness.
- Source Confusion.

WPRO testing

To test the basic profile-fitting system, a comparison with the WAP aperture photometry and the NEP mini-survey phtometry will be carried out. To test the deblending capabilities of WPRO, simulated data will be used to check both completeness and reliability of the photometry and error model. Since WPRO requires accurate PSFs, these tests will be predicated upon building accurate PSFs with the datasets available for testing. Some specific tests of WPRO will be:

Repeatability tests: Use multiple observations of the same region of sky, in order to check validity of estimated flux and position errors.

Behavior of chi squared: Make plots of reduced chi squared as a function of magnitude for each band, to check the validity of measurement error model.

Active deblending tests:

1. Verify performance using synthetic data for a variety of source separations, including sources which have significant flux in one band only. A particular case of interest is a weak Band 1-only source which is close to a strong Band 4-only source.

2. Determine optimal values of the parameters $(\chi^2_\nu)_{\rm crit}$ and $(\Delta\chi^2_\nu)_{\rm min}$.

Response to artifacts:

1. Examine the behavior of the solution in the vicinity of various possible artifacts, including saturated stars, diffraction spikes, latent images, and electronic crosstalk.

2. Examine the effeciveness of χ^2_ν for discriminating against spurious solutions and parameter estimates which have been contaminated by artifacts.

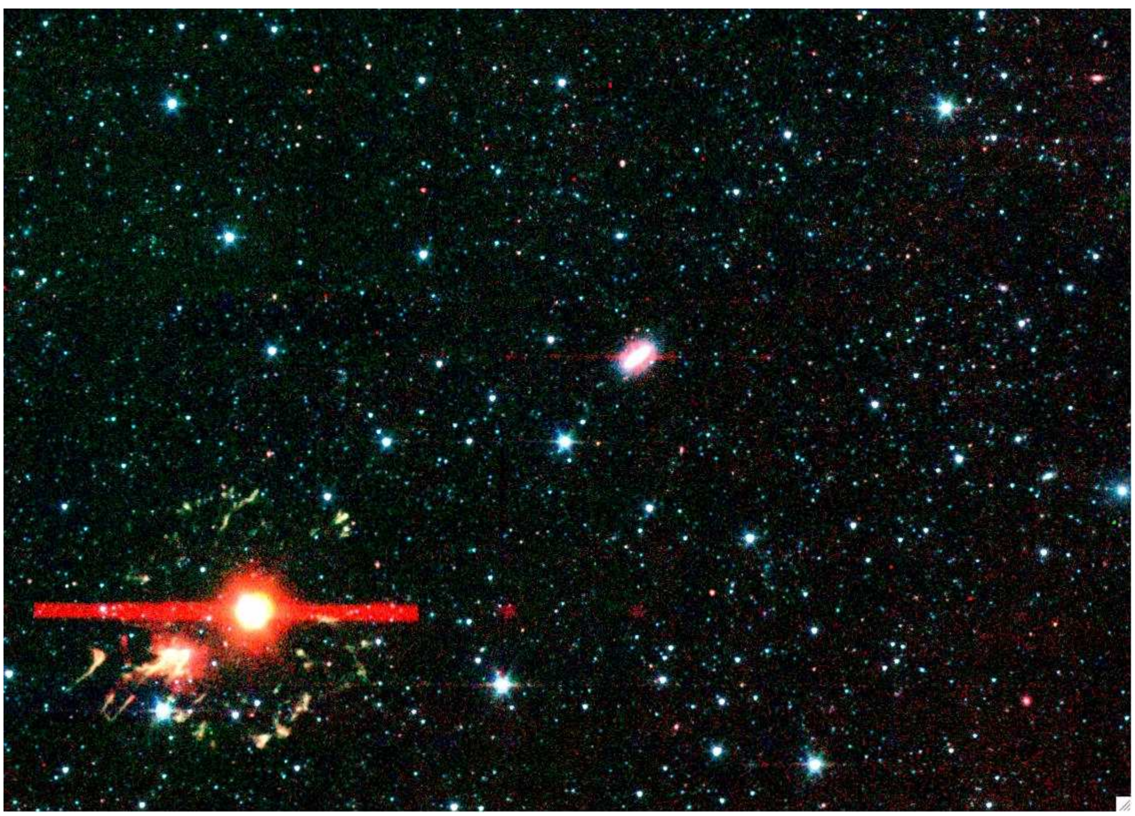


Figure 8: Center region of the NEP WISE-CVZ mini-survey by IRAC. The planetary nebula NGC 6543 ("Cats Eys") and barred galaxy NGC 6552 are prominent objects in the field.

7 Output List of Parameters

See the WPHOT.sis document.

8 REFERENCES

Bertin, E. & Arnouts, S. 1996, A&AS, 117, 393
Stetson, P. B. 1987, PASP, 99, 191

9 APPENDIX

9.0.7 Extended Sources and Advanced Characterization

Extended sources, in the form of fuzzy galaxies and Galactic nebulosity, will be present in every WISE image frame (e.g., see Fig. 5), thus complicating the primary mission goal of detecting, characterizing and cataloging point sources. The basic data reduction must include some level of extended source characterization to properly handle point source photometry and quality assessment of the resulting catalogue. A secondary issue is the scientific potential of the extended sources themselves. WISE will resolve hundreds of thousands of galaxies and its images will contain a rich assortment of Galactic emission, both high surface brightness and diffuse varieties. WISE data analysis is not scoped or budgeted to properly handle extended sources; consequently, additional source characterization (of extended sources) will be limited and confined to whatever resources are available. In the following we describe various measurements that may or may not be deployed; TBD.
The main issues to consider:

* Primary– Do we attempt to identify extended sources and (potentially) improve the point source photometry that is affected/contaminated by the extended emission?

* Secondary– Do we produce (and validate) images that have calibrated diffuse/extended emission? That is to say, is every pixel, whether it filled with Zody, or cirrus, or a piece of a galaxy have a calibrated surface brightness?.

* Secondary– Do we attempt to detect and characterize discrete extended sources (e.g., galaxies) ? Do we add these measurements into the WISE source catalog(s) ?

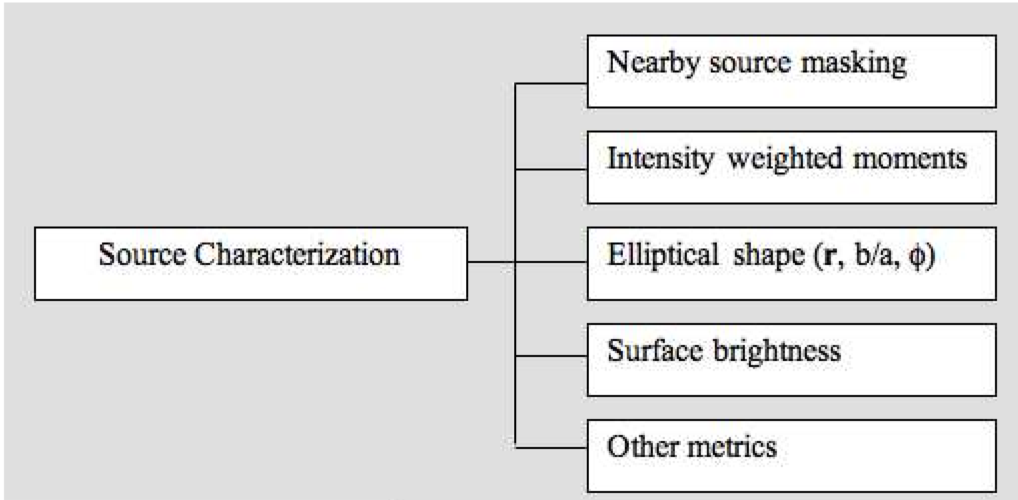
There are three basic kinds of resolved or extended sources: discrete, diffuse and a combination of the two. Examples include:

* discrete: galaxies, planetary nebulae, young stellar objects * diffuse: zodical emission, cirrus and Milky Way nebulosity * composite: HII regions, SNRs

There is some overlap between these rough categories. PNs may be more diffuse than discrete; some compact HII regions may be more discrete than diffuse; some galaxies are so diffuse that they are like whispy clouds in space. Zodical emission is so diffuse that it represents a smooth (but not necessarily uniform) background 'light' that will be in every WISE image. Observations that cross the plane of the Milky Way will potentially have every kind of extended source, thus presenting a major challenge for data reduction and source characterization.

At the very least, the WAPP system must have a way to measure the flux of discrete extended sources. Circular apertures that capture a significant fraction of the source light is the basic measurement. Consistent measurements from band-to-band ensure reliable color metrics. A corresponding size metric is another basic measurement. The size of the source determines how large the aperture measurements should be. To these ends, the local background must be measured to a high accuracy in order to remove residual light from the source fluxes.

Reliable fluxes, surface brightnesses and sizes require background, artifact and contaminating source subtraction to allow clean characterization and extraction. Total fluxes, in particular, require very careful image cleaning and subsequent characterization. The usual procedure is to



identify nearby stars and remove them by either masking them or subtracting their flux (using a PSF or some other simple model). With local source removed and the local background well determined, it is relatively straight-forward to characterize the discrete source. Complications arise when the source is asymmetric and/or diffuse and amorphous. It is unclear what can be done about Galactic diffuse and concentrated emission.
Considerations:

- What do we do about point source measurements that are contaminated by the underlying extended emission?
- To detect extended sources, will the standard point source detector be good enough? For 2MASS we used the same detector to find stars and galaxies, but fuzzies were then processed separately from point-like sources, thus creating two separate catalogues in the end.
- Alternatively, we do not attempt to detect extended source, but instead we use a prior list (e.g., 2MASS XSC & the MSX catalog) to locate and measure extended sources. We use prior measurements (e.g., 2MASS has a full set) to aide in the WISE characterization, thus easing the development resources.
- Do we add extended source measurements to the WISE source catalog? Do we create requirements (at least internally) for a catalogue, or just do a "best effort" and flag the sources accordingly in the WISE catalogue?
- How far do we carry the source characterization beyond simple aperture fluxes? Using a prior list (see above), we may be able to push harder with minimal development.
- Given the mind-boggling confusion and source complexity in the Plane, do we avoid it altogether for extended sources? For 2MASS, we worked in the Plane, but significantly ramped down our expectations (power-throttled by the confusion noise).
- How much are we willing to dedicate to extended source characterization? How much to diffuse measurements? To image cleaning?

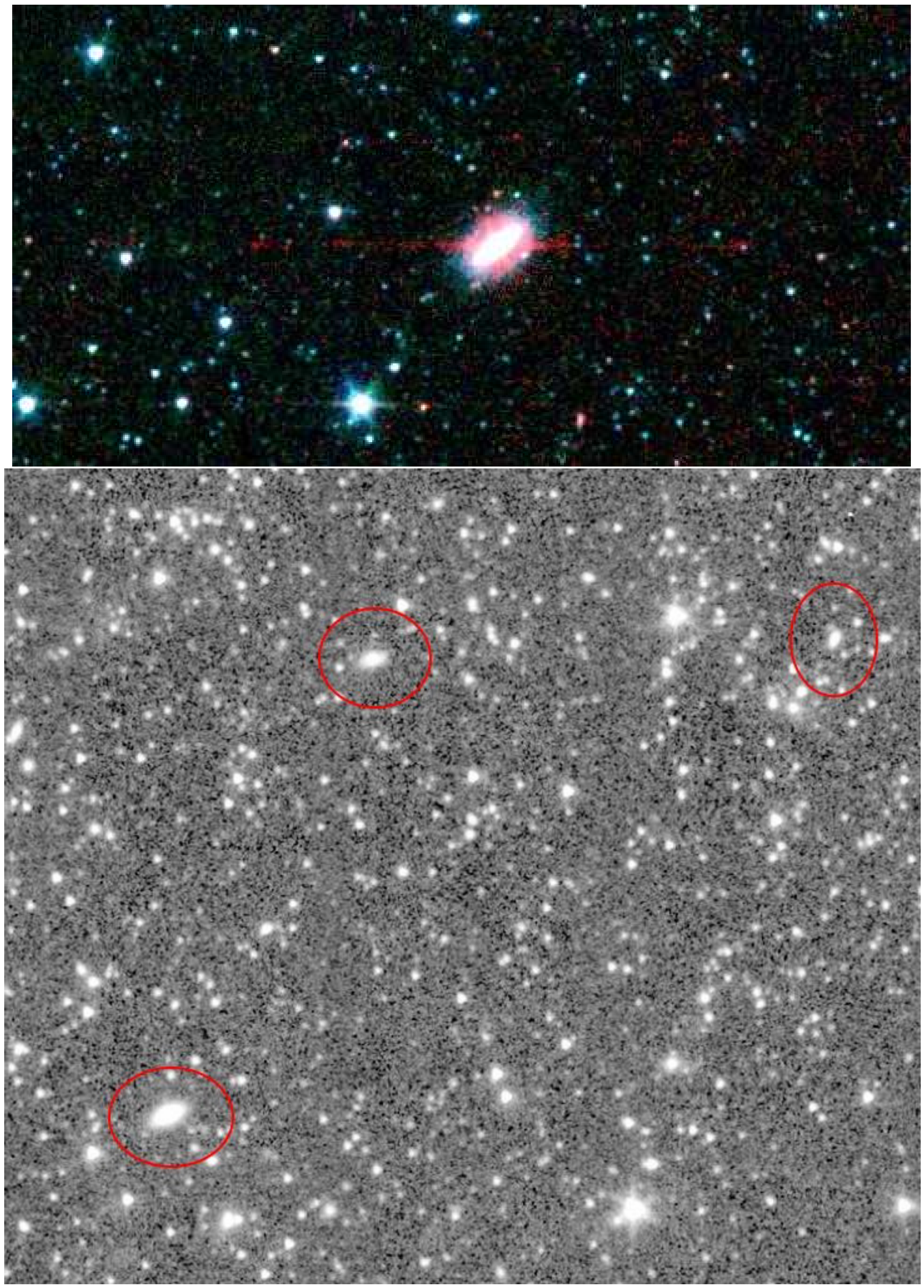


Figure 9: Upper panel: IRAC view of NGC6552 in the WISE NEP/CVZ. Lower panel: Resolved galaxies in a SWIRE 3.6um image of the Lockman Hole