SIMPLE—An IDL Based Data Reduction Pipeline for Wide-Field Near-Infrared Imaging

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ABSTRACT

The SIMPLE Imaging and Mosacking Pipeline (SIMPLE) is an Interactive Data Language data reduction environment designed for wide-field near-infrared imaging data obtained from ground-based mosaic cameras. It is currently optimized for blank-field extragalactic surveys where there are no large extended objects. SIMPLE provide basic reductions functions including dark subtraction, and various ways of flat fielding and background subtraction. It features a robust flat fielding that is iteratively derived from dithered night sky images and leads to extremely flat images after a simple background subtraction. SIMPLE automatically corrects for image distortion in a set of dithered images, without any prior knowledge about the optics and without any astrometric catalogs as inputs, allowing for accurate registrations of wide-field images. After combining the distortion corrected images and projecting the image, SIMPLE regularly achieves absolute astrometry that is better than $0\farcs1$ and even $0\farcs02$ (rms). Current SIMPLE distributions are optimized for two mosaic cameras on Mauna Kea: MOIRCS on the 8 m Subaru Telescope and WIRCAM on the 4 m Canada-France-Hawaii Telescope. However, the SIMPLE subroutines are written as generally as possible and the reduction pipelines can be modified for other similar cameras with reasonably small amounts of efforts.

Subject headings: Data Analysis and Techniques

1. Introduction

In the last decade, mosaic cameras consisting of two to tens of CCD chips or infrared sensors have become increasingly popular on ground-based telescopes. They provide simultaneous field of views from a few arc minutes to approximately an arc degree and they greatly improve the efficiency for galactic and extragalactic surveys. However, processing data from mosaic cameras

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is not trivial. One of the fundamental challenges comes from the distortion of the optics, which may be negligible in small field of views but prevents uniform astrometric quality over the very large field of views of the mosaic cameras, i.e., the dithered images from mosaic cameras can no longer be simply shifted and combined for a deep integration. The distortion issue is also coupled to flat fielding and prevents uniform photometry across a very wide field. The orders of magnitude increase in data size also require different approaches than the conventional reduction of small-field images.

The SIMPLE Imaging and Mosaicking Pipeline (SIMPLE) is an Interactive Data Language (IDL) pipeline developed to address the above issues for wide-field mosaic camera images. Historically, the development started in early 2005 for images taken with the Ultra Low Background Camera (ULBCAM, Hall et al. 2004) on the University of Hawaii 2.2 m telescope. The ULBCAM consists of 4 2048×2048 HgCdTe near-infrared arrays and is the first large-format near-infrared mosaic camera. The SIMPLE development focus gradually shifted to other cameras on larger telescopes since 2006. The latest stable releases of SIMPLE feature subroutines that perform general reduction tasks, and two reduction pipelines that are highly optimized for two near-infrared mosaic cameras: the Multi-Objects InfraRed Camera and Spectrograph (MOIRCS, 2 2048×2048 HgCdTe arrays, $0\farcs117$ pixel scale, Ichikawa et al. 2006) on the 8 m Subaru telescope and the WIRCAM (4 2048×2048 HgCdTe arrays, $0\farcs306$ pixel scale, Puget et al. 2004) on the 4 m Canada-France-Hawaii Telescope (CFHT). At this moment, the two pipelines are designed for dithered exposures of blank-field extragalactic surveys. However, with suitable treatments to sky background in the background subtraction and image combination stages, it is possible for SIMPLE to process galactic images. It should be also fairly easy to modify the existing MOIRCS or WIRCAM pipeline to process images obtained with other similar cameras in the optical and near-infrared. All SIMPLE elements are made open to the community so the users can modify the pipelines according to their needs. The user manuals and the packages are available on the web[3].

This paper presents the most important features of SIMPLE, the algorithms, and restrictions in its functions. Fig. 1 is a schematic diagram showing the processing flow of the SIMPLE MOIRCS and WIRCAM pipelines. § 2 describes the basic requirements of SIMPLE. § 3 to §9 describe the algorithms and the processing details in the diagram of Fig. 1. § 10 discusses the quality of the SIMPLE reductions. § 11 is a summary.

Throughout the paper, CFHT WIRCAM and Subaru MOIRCS observations of the GOODS-N field in J and K_s bands are used to demonstrate the quality of SIMPLE reductions. The WIRCAM J band imaging was carried out by Lihwai Lin (2008, in preparation) in the semester 2006A and the data were obtained from the CFHT public archive. The image includes approximately 9 hr of integration covering a $28' \times 28'$ field centered at the Hubble Deep Field-North (HDFN). The WIRCAM K_s band imaging was carried out by Luc Simard in 2006A and by Lennox Cowie in 2006A and 2007A. The image includes approximately 40 hr of integration covering an area of

[3]http://www.aoc.nrao.edu/∼whwang/idl/SIMPLE/

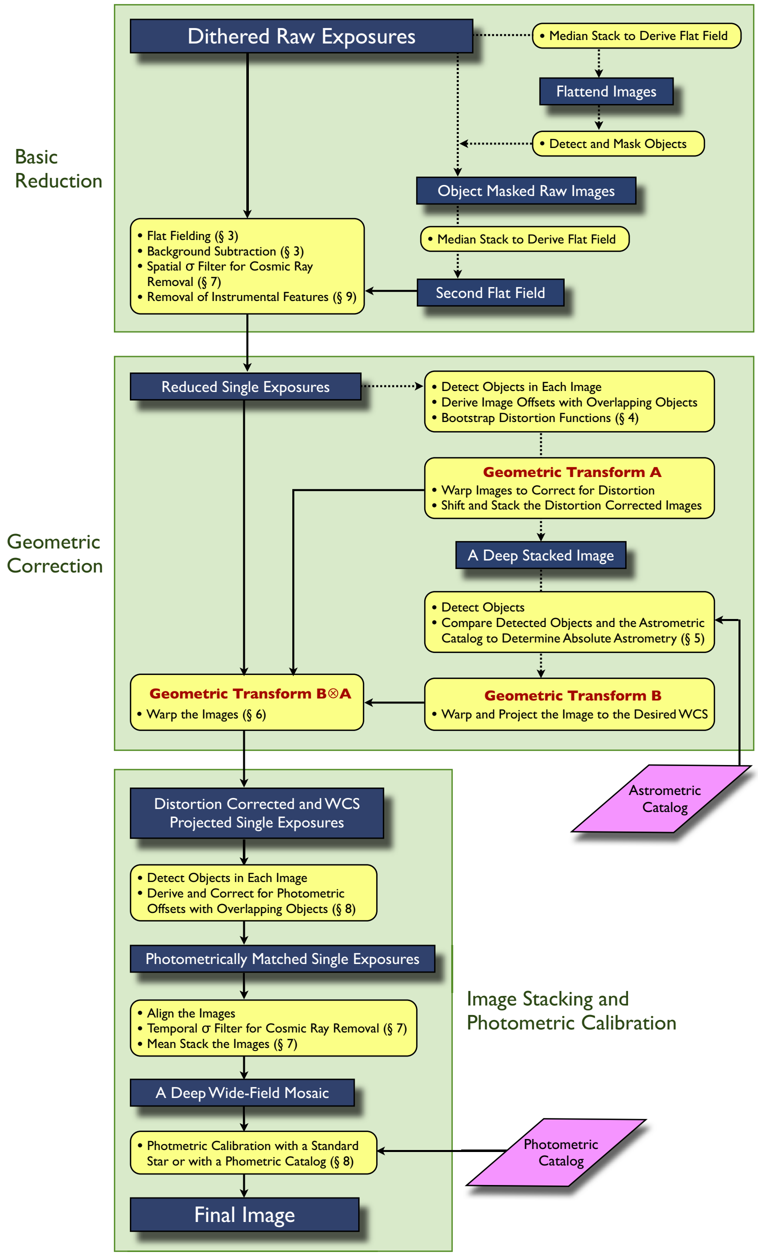

Fig. 1.— Flowchart of the SIMPLE WIRCAM and MOIRCS pipelines. Blue squares are data products at various processing stages. Yellow rounded squares are the processes and the associated sections in this paper. The two external catalogs required for astrometric and photometric calibrations are the pink diamonds. Dotted arrows indicate iterative processes whose data products will not be directly used in the next stages of processes.

$31' \times 31'$ centered at the GOODS-N. The SIMPLE reduction of this deep K_s image is used in the Hawaiian multi-year imaging and spectroscopy campaign in the GOODS-N and is published in Barger, Cowie, & Wang (2008). The MOIRCS K_s band imaging of the GOODS-N was carried out by various Japanese PIs and Lennox Cowie in Hawaii between Jan 2005 and Jan 2008. The SIMPLE reduction includes all Hawaiian data and the public Japanese data from the Subaru archive, with a total of ~ 35 hr of observations distributed in ~ 20 pointings with various position angles and various amounts of overlaps, covering an area of $\sim 12' \times 18'$, nearly the entire GOODS-N. These data taken by different groups with different strategies were successfully processed by SIMPLE into a single large mosaic image. The SIMPLE reduction of the MOIRCS data was used in Wang, Barger, & Cowie (2009) and Barger et al. (2008). To give the readers a rough idea about these data, Fig. 2 presents the low resolution WIRCAM and MOIRCS images.

2. Basic Scientific and Software Requirements

SIMPLE assumes that all exposures are dithered. Many of the SIMPLE features rely on this, including flat fielding, background subtraction, distortion correction, and cosmic ray removal. Although it is possible to process undithered images in SIMPLE, dithering is highly recommended. The default mode of the SIMPLE WIRCAM and MOIRCS pipelines is to reduce and combine images from the same sensor within one dither set, and then later to combine the results from different sensors and multiple dither sets into a large mosaic. Although SIMPLE does not require external information other than the dithered images for distortion correction and accurate image registration, an astrometric catalog is required for the absolute astrometric calibration. Photometric calibration is carried out with either standard star observations or a photometric catalog. SIMPLE makes extensive uses of the IDL Astronomy User's Library (Landsman 1993)[4] and the package SExtractor (Bertin & Arnouts 1996), both needed to be installed along with IDL itself.

3. Flat Fielding and Background Subtraction

Flat fielding and background subtraction are two highly coupled issues in near-infrared data reduction. Two methods are supported in SIMPLE. The first is to use dome flats (or twilight sky flats). In principle, dome flats have light sources that are approximately black-body continuum and have colors similar to galaxies and stars, which is an advantage. On the other hand, the colors of dome flat sources can be quite different from the sky, which is dominated by atmospheric emission lines and whose color is highly variable in a time scale of tens of minutes. Therefore, dome flattened images almost always have complex residual structures in the image background. To remove such a background, SIMPLE first masks all detected objects in dithered images, and then derives a

[4]also see http://idlastro.gsfc.nasa.gov/

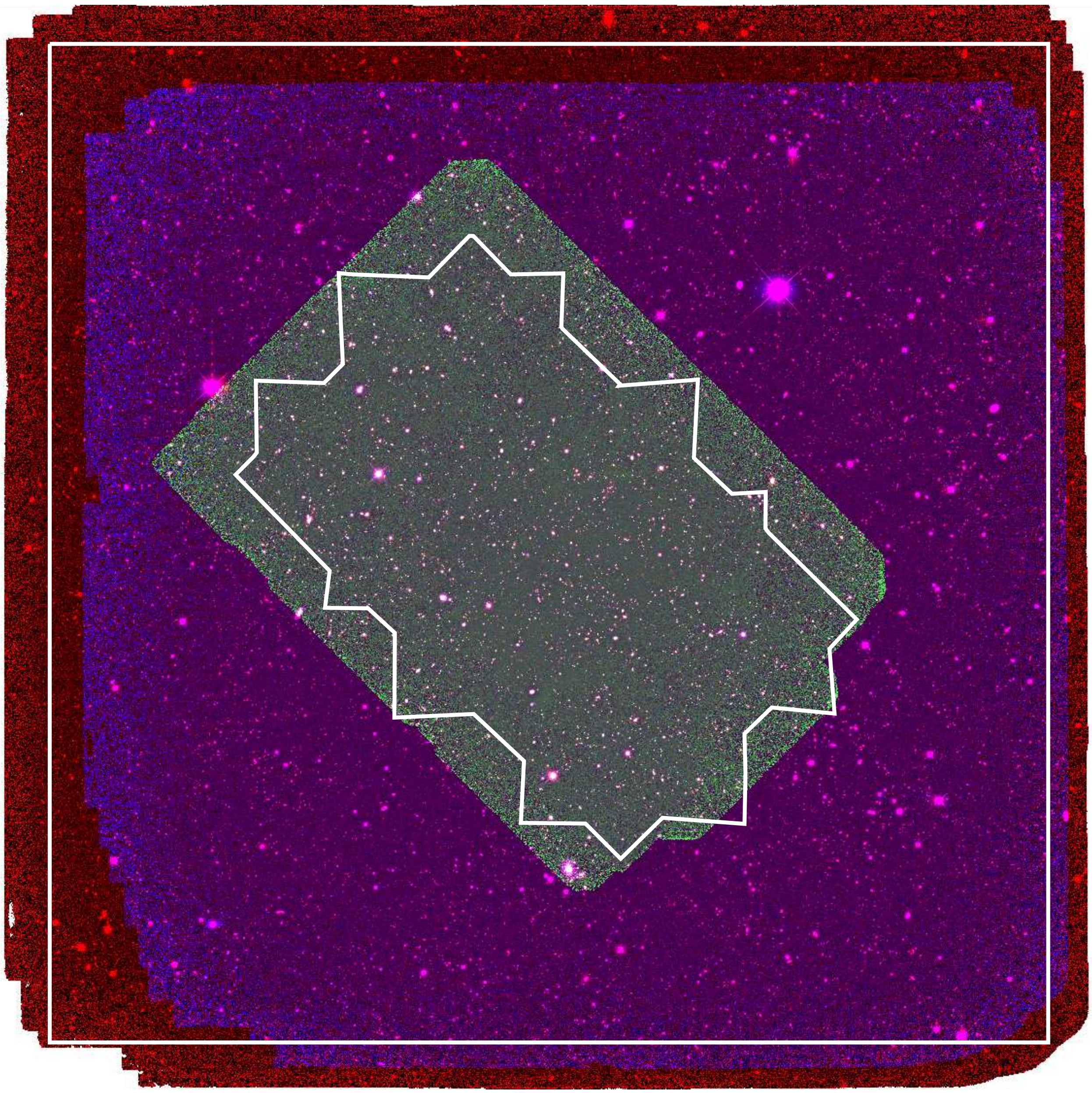

Fig. 2.— GOODS-N images used in this paper to demonstrate the quality of SIMPLE reductions. The red is the WIRCAM K_s image. The green is the MOIRCS K_s image. The blue is the WIRCAM J image. The polygon shows the *HST* ACS area of the GOODS-N and the large box has a size of $30' \times 30'$. The distributions of the integration times of the two WIRCAM images are relatively uniform. The MOIRCS integration time distribution is highly non-uniform, with roughly 2/3 of the integration concentrated in a ~ 40 arcmin^2 area around the HDFN.

background model from the mean or median of the object masked images.

The second and the standard flat-fielding provided by SIMPLE is to use an iterative night-sky flat. A flat field model is first derived with the median of the dithered images, typically taken within a period of roughly half hour. After all the dithered images are flattened with the initial flat field, objects are detected in the flattened images and masked in the raw images. The masked raw images are normalized, taking into account the positions of the masks, and then a second flat field model is derived with the median or mean of the masked images. This iterative masking process cleanly removes the footprints of most celestial objects in the flat fields. Only in extremely deep (tens of hours) integrations, the footprints of objects start to appear in the form of faint negative halos around bright galaxies with shapes of the dither pattern. Such artifacts can be minimized by mixing various dither patterns during the observations and generally do not affect the photometry of faint and compact galaxies. Since the flat fields are derived from the sky itself during the actual period of the observations, this method often provides extremely flat sky backgrounds. Because the near-infrared color of the sky changes in time scales of tens of minutes, it is possible that there are still some residual sky structures in a dither set of roughly half hour in length. Such residual structures are usually very weak and smooth, and can be easily removed from each image by fitting a polynomial surface after detected objects are masked.

4. Relative Astrometry and Distortion Correction

One of the most important feature of SIMPLE is the ability to correct the optical distortion internally and to stack dithered images accurately without external information (astrometric catalogs or distortion function of the optics). The first step is to detect objects (stars and compact galaxies with sufficient S/N) in each image and to find overlapping objects between the dithered images. The source detection and measurements of source positions rely on SExtractor. The identification of overlapping objects relies on the coarse pointing information provided in the image headers. (This can also be done with 2-D cross-correlation without using the headers.) More accurate offset values between the images are then derived from the overlapping objects.

The SIMPLE distortion correction is inspired by the method described by Anderson & King (2003) for WFPC2. It is slightly simplified here because of the less demand in ground-based observations. SIMPLE adopts cubic polynomials for the distortion functions, i.e.,

$$x' = F(x, y) = \sum f_{ij} x^i y^j, \tag{1}$$

$$y' = G(x, y) = \sum g_{ij} x^i y^j, \tag{2}$$

where x and y are the undistorted coordinates, x' and y' are the distorted coordinates, F and G are the distortion functions, and $i + j \leq 3$. To the first order, the displacements of objects between dithered images can then be expressed as the expansions of the distortion functions:

$$\Delta x' = \frac{\partial F(x, y)}{\partial x} \Delta x + \frac{\partial F(x, y)}{\partial y} \Delta y \tag{3}$$

$$\Delta y' = \frac{\partial G(x,y)}{\partial x}\Delta x + \frac{\partial G(x,y)}{\partial y}\Delta y, \tag{4}$$

where $\Delta x'$ and $\Delta y'$ are the measured displacements of stars, which are functions of positions, and Δx and Δy are the pointing offsets of the dithering. It is now clear that under the approximation the measured displacements of stars are the first order derivatives of the distortion functions. For n overlapping objects between m dithered images, there are approximately $n \times (m-1)$ sets of linear equations for each of $\Delta x'$ and $\Delta y'$. The systems of linear equations are solved for the coefficients of F and G with a least-square method. Initially, the mean values of $\Delta x'$ and $\Delta y'$ are used as approximates of Δx and Δy. After F and G are integrated, they are used to correct for x' and y' and to derive better estimates of the dither offsets Δx and Δy. Then improved coefficients of F and G are solved with the new Δx and Δy. For the small distortions of MOIRCS and WIRCAM, one iteration can provide sufficiently good distortion functions. For larger distortions, it may require more iterations and perhaps require even higher order terms in both the polynomial form of the distortion functions and in their expansion. At this moment, higher order distortion functions and expansions are not supported in SIMPLE, but will be implemented in the future versions.

The approach described above has several advantages. First, the distortion function can be reasonably measured out to the edges of the field of view as long as there are detected objects. This is sometimes not the case if the distortion function is derived by comparing detected objects with an external astrometric catalog. In many cases, the external catalog (e.g., USNOB-1 or SDSS) is not as deep as even a single exposure on large telescopes. Sometimes there are not enough cataloged objects in some regions of the dither images (though there are still plenty of detected objects), and this makes the derived distortion function less reliable in such regions. Deriving the distortion function internally from each dither set also overcomes flexure of the telescope, which can be time dependent and is common on large ground-based telescopes. Computationally, there is very little to pay since the most time consuming process is to detect objects in all the images, which is required for measuring offsets between the dithered images nevertheless.

From the equations presented here, it is clear that this internal approach and the first order approximations require dither steps that are small enough comparing to the sensor size (also depending on the amount of distortion). The default dither patterns provided by WIRCAM and MOIRCS all satisfy this and SIMPLE reductions of archived data taken by various groups with different strategies have not failed at this step. Experiments show that robust solutions for the distortion function can be derived with just 5–7 properly dithered images from WIRCAM or MOIRCS. It remains to be tested if even smaller numbers of dithered images can provide good solutions. Fig. 3 shows an example of the distortion function and array geometry of WIRCAM derived by SIMPLE.

Finally, in the rare situation where the images are not dithered or there only exits one image, it is still possible for SIMPLE to use the conventional method of comparing detected objects with an astrometric catalog for distortion correction. This is embedded in the sky projection step described in the next section.

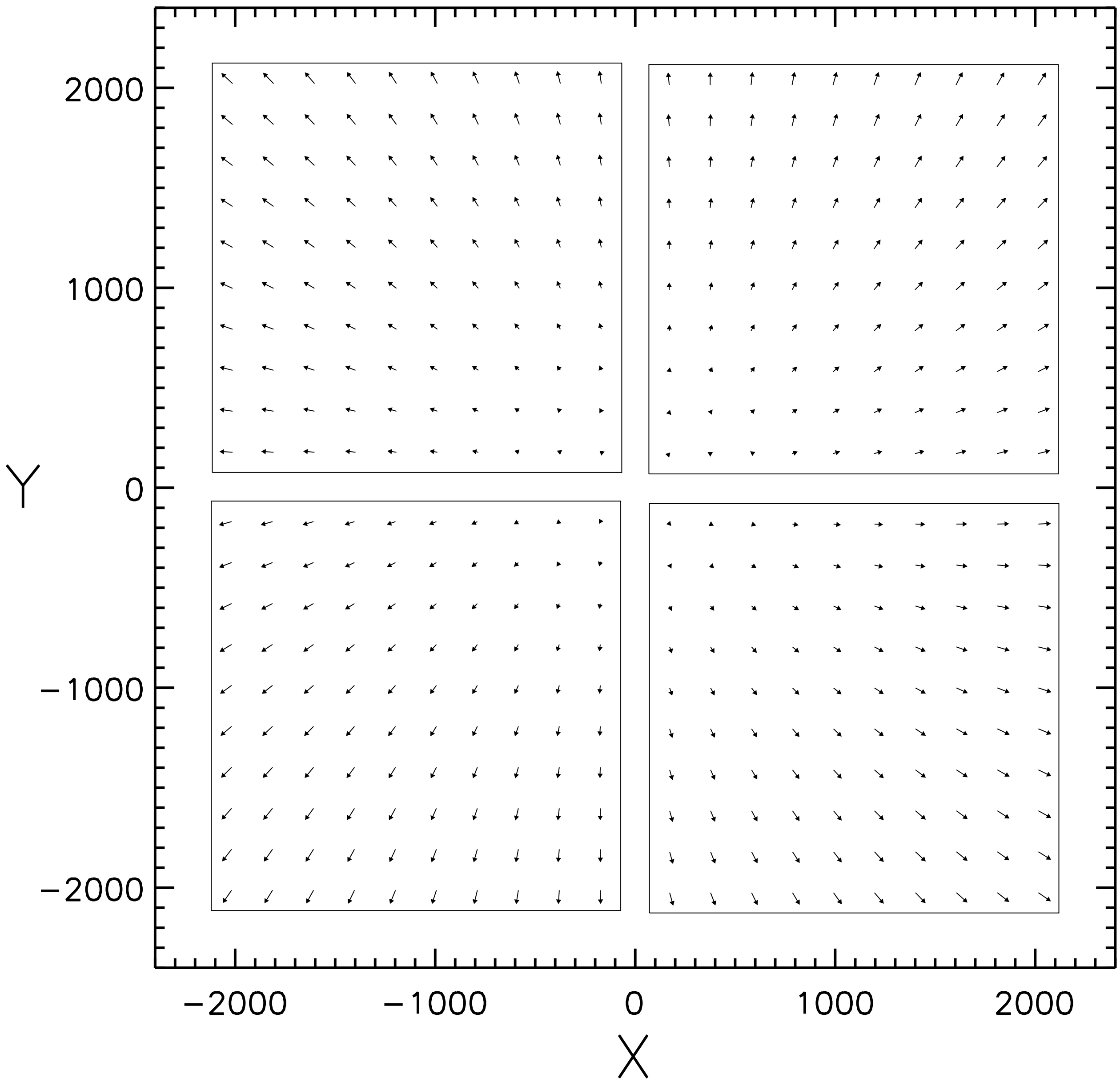

Fig. 3.— Array geometry and distortion function of WIRCAM derived by SIMPLE from a set of dithered image. The axes are pixel coordinates. The pixel scale is measured by SIMPLE be $0\farcs3044$ at the array center for this data set. The large boxes outline the locations of the four 2048×2048 arrays on the focal plane. SIMPLE detected small amounts of misalignments between the four, which is too small to be seen on this plot. The vectors show the optical distortion, with a magnification of $2\times$. The largest offsets (at the four corners) measured from this particular dither set are ~ 38 pixels (1.28% the distance from the array center).

5. Absolute Astrometry and Sky Projection

An external astrometric catalog is required to obtain absolute astrometry for the distortion corrected images. Once the distortion is taken care of, it requires relatively few stars for absolute astrometry. The function that projects the distortion corrected images to the sky is also relatively simple, as long as the image size (from the projection center) is smaller than a few degrees. The minimum requirement for the astrometric catalog is 3 stars in each sensor, since the above distortion correction does not guarantee equal image scales along x and y. Extremely good sky projection and absolute astrometry can be achieved with a second or third order polynomial image warping and with 10 to 20 stars that are more or less uniformly distributed over the field of view of a sensor. The users can specify the pixel scale, projection center, and rotation angle of the final world coordinate system (WCS) for the final reduced images. When projecting the images to the specified WCS, SIMPLE only supports the gnomonic (tangential) projection, but it is very easy to include other commonly used projections. In the projecting and resampling process, SIMPLE always makes the projection center have integer pixel coordinates. In case many reduced images need to be later combined into a larger or deeper mosaic, this ensures that the images only need to be shifted for integer amounts of pixels to be properly combined and no further resampling is needed, as long as the images share the same WCS.

It is useful to realize that the astrometric catalogs are not limited to the standard catalogs such as USNOB-1 or SDSS. In the SIMPLE reductions of GOODS-N and GOODS-S images from MOIRCS and WIRCAM, *HST* ACS source catalogs are used whenever available, and the reduced images have object positions extremely well matched to the space-based source positions. In the reduction of the MOIRCS images ($\sim 0\farcs1$ pixel scale and $0\farcs4$ typical seeing), the difference between source positions in the final image and in the reference catalog is $\lesssim 0\farcs02$ rms. The astrometric accuracies of SIMPLE reductions are mostly limited by the quality of the input astrometric catalogs, and to a less degree the image quality of the observations. § 10 presents more detailed analyses on the astrometric performance of SIMPLE.

6. Resampling and Flux Conservation

The procedures described in the previous two sections seem to involve two resampling, one for correcting the distortion and the other for projecting the distortion corrected images onto a certain WCS. To minimize the impact to the image quality and the noise correlation between pixels, SIMPLE combines the two resampling functions into one and directly warps the original images to sky-projected ones (see the “Geometric Correction” section in Fig 1). SIMPLE simply adopts the bilinear resampling provided in IDL. It is possible to use the IDL bicubic resampling but not for other more advanced resamplings at this moment. The adopted bilinear interpolation in SIMPLE introduces 10% to 20% increase in image FWHM when the seeing PSF is nearly Nyquist sampled (see discussion and an example in § 10).

When images are warped in SIMPLE, there is an option for correcting for the changes in pixel sizes to conserve surface brightness. This is performed by computing the Jacobian of the transformation function

$$\Delta x'\Delta y' = \begin{vmatrix} \dfrac{\partial F}{\partial x} & \dfrac{\partial G}{\partial x} \\ \\ \dfrac{\partial F}{\partial y} & \dfrac{\partial G}{\partial y} \end{vmatrix} \Delta x \Delta y, \tag{5}$$

where $\Delta x\Delta y$ is the original pixel size, $\Delta x'\Delta y'$ is the new pixel size, and F and G are the transformation functions between the new and the original systems. The Jacobian is computed for each pixel and divided from the pixel values.

It is important to point out that there is a coupling between flat field and optical distortion. The above Jacobian correction is only necessary for resampling images that are "properly" flattened where the photometry is uniform across the entire image. In the SIMPLE reductions of MOIRCS and WIRCAM images, the Jacobian is *not* applied to the images for flux conservations. This is because the change in the optical illumination pattern produced by the distortion is "mistakenly" removed by flat fielding. Warping the images into a distortion-free frame without the Jacobian correction can correct for this mistake and restore the correct surface brightness to the pixels. There is also a subtlety of what is a distortion-free frame (see the discussion in Anderson & King 2003). SIMPLE simply assumes that the tangentially projected WCS is a distortion-free frame. At $\theta = 2^\circ$ from the projection center, $\partial \tan(\theta)/\partial\theta$ is 1.0012, translating to an photometric error of 0.0026 mag, which is negligible in almost all cases of wide-field ground-based surveys. Since it is rare to create image that is much larger than 2° from the projection center, there is practically no difference between a tangentially projected image and an ideal distortion-free image in terms of surface brightness.

7. Image Combination, Weighting, and Cosmic Ray Removal

The distortion corrected and projected images are mean combined in SIMPLE to create deep mosaic images. SIMPLE does not provide the option of median combination as its S/N is lower than that of a mean combination by a factor of $\sqrt{\pi/2}$, which translates to a very expansive 58% decrease in effective integration time. In order to remove outlier pixels (e.g., cosmic ray hits), SIMPLE provides the option of temporal σ clipping prior to the mean combination. Pixels with identical projected coordinates (from exposures taken at different times) are compared with each other and outliers are excluded before the mean is computed. To remove cosmic rays in the outer parts of the images where there are no enough overlapped exposures for the temporal σ filtering, a spatial σ filtering is used on each individual exposure to remove the brightest cosmic ray. Visual inspection shows that the combination of temporal and spatial σ filters is very effective in removing cosmic rays.

When several images are combined, SIMPLE can simply weight each image by its exposure time. For each combined image, SIMPLE produces a corresponding exposure time map, which can be used for future mosaicking (to form even deeper or wider mosaic images) or used as a weight map in scientific analyses. Alternatively, SIMPLE can weight *each pixel* according to its exposure time, extinction, quantum efficiency (i.e., flat field), and sky background. The exact weight applied to a pixel is

$$w(x,y) \propto \eta^2 T_{\rm exp} B G^{-1} Q_{\rm E}(x,y). \tag{6}$$

The atmospheric transparency η is calculated based on the zenith photometric zero point measured from standard star observations or from a photometric catalog (§ 8), and the airmass assuming the Mauna Kea extinction measured by Leggett et al. (2006). All the factors in the weights are kept tracked by SIMPLE automatically. When significant fractions of the observations have very high or very low sky backgrounds, or when the sensors of the mosaic cameras have significantly different quantum efficiencies, this more optimized weighting scheme can produce S/N that is more than 5% higher than the standard one.

At this moment, "drizzle" (Frutcher & Hook 2002) is not supported in SIMPLE as most ground-based observations are not terribly limited by pixel resolution. However, a preliminary test shows that it is possible to implement drizzle under the SIMPLE framework. Whether or not to implement drizzle in the future versions will likely depend on the amount of user requests.

8. Flux Calibration

In the image combination stage, SIMPLE can use overlapping objects in the images to calibrate the relative flux scales of the images. This is necessary for data obtained under nonphotometric conditions. For absolute flux calibration, the users can choose to observe a standard star with matched filters, or to use existing photometric database (SDSS, 2MASS, or the alike) when the photometric system of the observations is sufficiently similar to that of the database. SIMPLE uses SExtractor for flux measurements. The users can choose to use fixed apertures or the SExtractor auto apertures. Fig. 4 shows calibrated (with 2MASS) WIRCAM K_s fluxes vs. 2MASS fluxes in the GOODS-N field. Generally speaking, the SIMPLy reduced WIRCAM fluxes compare well with the 2MASS fluxes in the range of $\sim$ 1–8 mJy. Below this range there are selection effects in the 2MASS fluxes. Above this range WIRCAM becomes nonlinear[5]. The exact calibration is thus sensitive to the choice of the magnitude range.

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[5]Linearity corrections (provided by C.-H. Yan, 2008, personal communication) for WIRCAM images are optional in SIMPLE. Limited amount of experiment shows that the correction does not greatly improve the comparison between WIRCAM fluxes and 2MASS on bright stars.

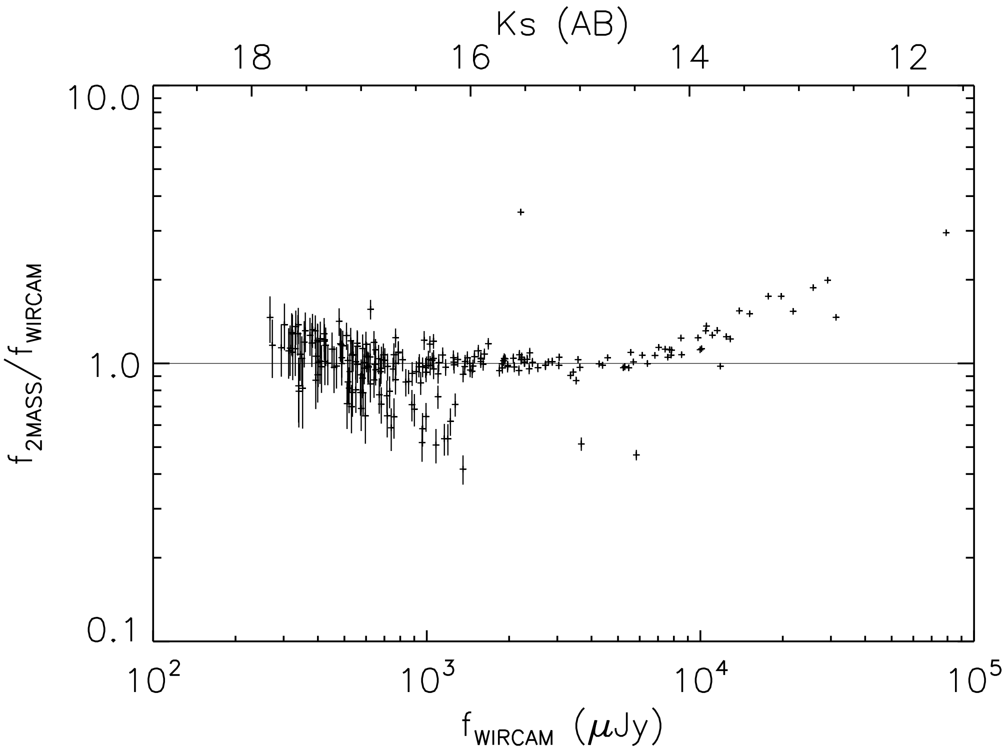

Fig. 4.— Comparison between 2MASS-calibrated WIRCAM K_s fluxes and 2MASS K_s fluxes of 2MASS objects in the GOODS-N field. The WIRCAM K_s images were reduced without corrections for linearity[5]. The ratios between the WIRCAM and 2MASS fluxes are flat between 1 and 10 mJy and the scatter is consistent with the magnitude errors in 2MASS . At $\gtrsim 8$ mJy, WIRCAM becomes nonlinear. At < 1 mJy, there are selection effects in the 2MASS fluxes.

9. Instrument Dependent Features

The MOIRCS and WIRCAM versions of the SIMPLE pipelines provide the handling of two features unique to these cameras. MOIRCS data taken before 2008 suffer from fringes caused by the excellent surface accuracy of its filters (Fig. 5). The fringes are nearly perfect circles in the images. SIMPLE first masks detected objects in a flattened and background subtracted image, and then transforms the image into polar coordinates where fringes are straight lines. Fringes are modeled in the polar system, transformed back to the Cartesian system, and then subtracted from the image. This effectively remove almost all fringes except for the most severe ones. New MOIRCS observations do not have fringe problems and the SIMPLE defringing task can be useful for processing archived data.

In WIRCAM data taken before early 2008, there is crosstalk among the 32 readout channels. Bright stars produce positive and negative ghost images, some are confined to 8 neighboring channels on the same video board and some exist in all of the 32 channels. To remove the crosstalk

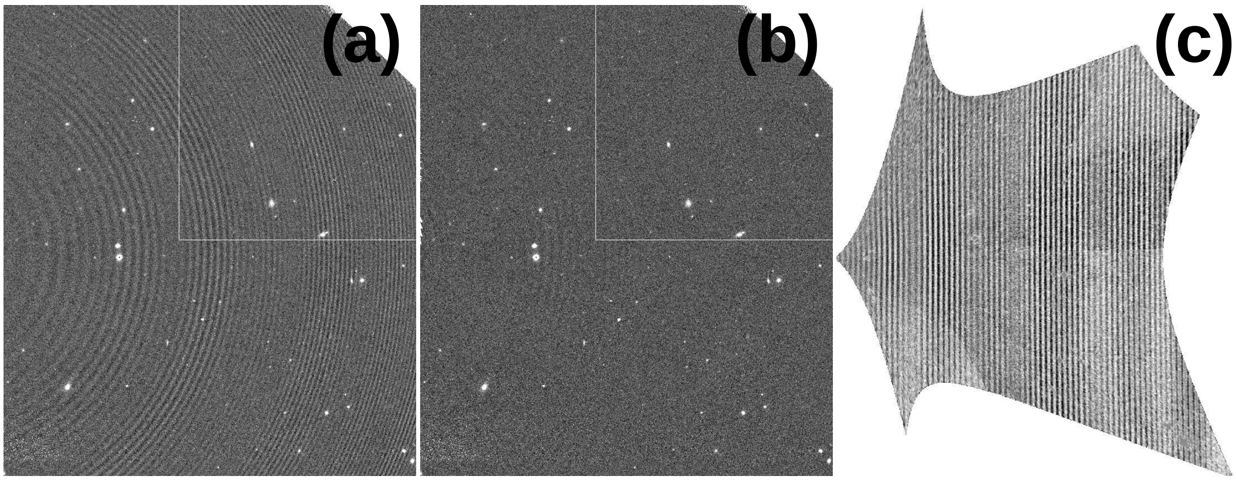

Fig. 5.— An example of SIMPLE removal of MOIRCS fringes. (a) A flattened and background subtracted 100 sec K_s band exposure. (b) The same image after SIMPLE defringe. (c) Same as (a) but in polar coordinates. This is not a typical example and is probably one of the worst cases. Most MOIRCS exposures do not look as bad and the fringes can be removed by SIMPLE cleanly.

effects from the WIRCAM images, SIMPLE adopts the method developed by Lennox Cowie (2006, personal communication). SIMPLE first masks bright objects on a flattened and background subtracted image, makes a median image from the 32 64×2048 channels, and then subtracts the median from each of the 32 channels. After the subtraction of the 32-channel median, brightest objects still have low level residual effects in the 8 neighboring channels that only show up in very deep integrations. To remove this, subtraction of 8-channel medians is performed around bright objects. The combination of the 8 and 32-channel medians effectively remove all crosstalk and no residual effects are observed around moderately bright stars in deep integrations of 10 to 20 hours (Fig. 6).

10. Quality of SIMPLE Reductions

A rough sense about the SIMPLE photometric uniformity can be obtained by comparing SIMPLE reductions of totally different data sets in the same field. Fig. 7 compares the fluxes in the SIMPLE reduced WIRCAM and MOIRCS K_s images of the GOODS-N. The WIRCAM fluxes were calibrated with 2MASS objects in the image (Fig. 4) and the MOIRCS fluxes were calibrated with nightly observations of UKIRT Faint Standards (Hawarden et al. 2001; Leggett et al. 2006). The MOIRCS image was convolved with a Gaussian kernel to match the image quality in the WIRCAM image and fluxes in both images were measured with fixed $3''$ apertures. It can be seen that the flux ratios are flat over a very wide range. Above 20 μJy (where the photon noise is negligible), the rms scatter of the flux ratios is a very good 0.042 mag, suggesting an up

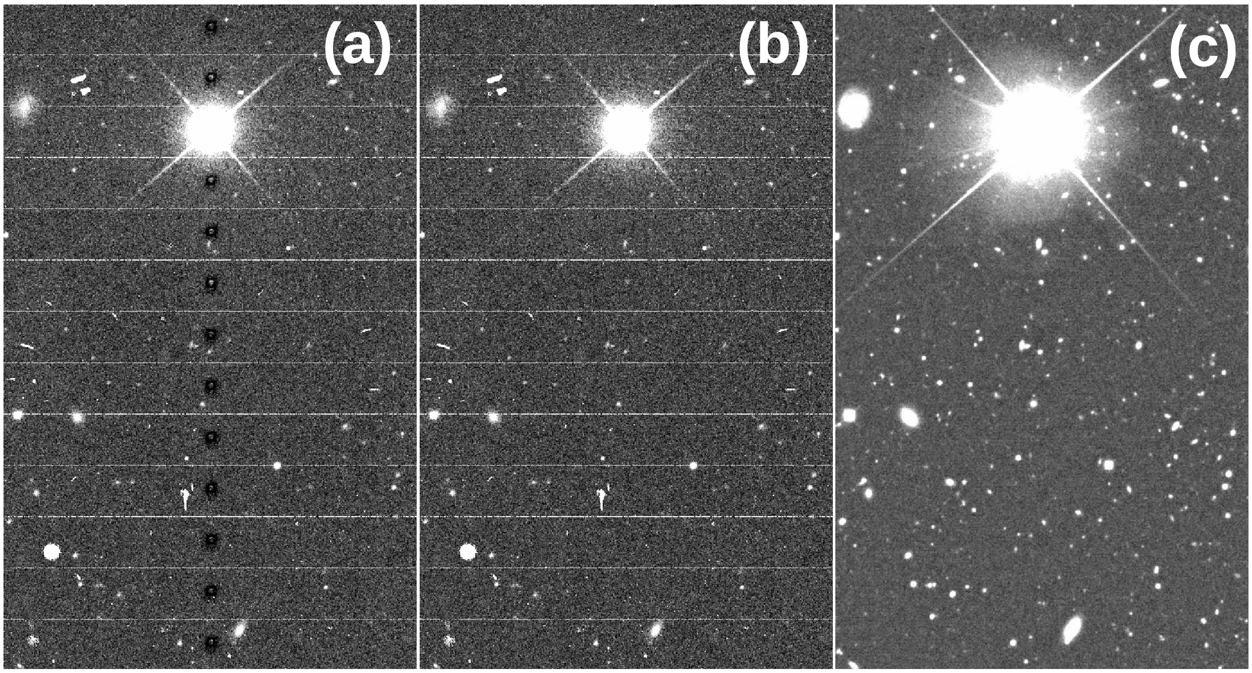

Fig. 6.— An example of SIMPLE removal of WIRCAM crosstalk. (a) A flattened and background subtracted 170 sec J band exposure. The bright star is the one to the northwest of the GOODS-N (see Fig. 2) and has a J band 2MASS magnitude of 8.34. (b) The same image after SIMPLE decrosstalk. (c) A 9-hr deep integration of the same region. All the data were taken in the semester 2006A when crosstalk was still a serious issue on WIRCAM. It can be seen that the crosstalk is cleanly removed and there are no residues showing up in the deep integration.

to 0.03 mag of systematic error in each image over the entire $18' \times 12'$ area of GOODS-N. (The MOIRCS observations were carried under a range of seeing conditions and there is a slight variation of image quality over the entire MOIRCS field of view. Hence the convolution of a Gaussian kernel for the entire image does not provide a uniform FWHM match. This also slightly contributes to the observed scatter between WIRCAM and MOIRCS, but is not an issue in the reduction quality.) The small scatter observed here indicates excellent qualities in the SIMPLE flat fielding, background subtraction, and relative calibrations between each sensor of the mosaic cameras and between each observing run. On the other hand, given the small dynamic range available in the K_s 2MASS/WIRCAM calibration discussed in § 8 and Fig. 4, it is a nice surprise that 2MASS and UKIRT Faint Standards provide calibrations that are well within 2% between these two cameras.

When SIMPLE projects distortion corrected images onto the sky and calibrates the absolute astrometry using a reference astrometric catalog, extra degrees of freedom are added to the image warping to force the object positions matching the catalog as tightly as possible. By doing so, the astrometry in the reduced image is almost entirely determined by the quality of the input catalog and to a less degree the image quality. Examples in Fig. 8 show that rms scatter between the

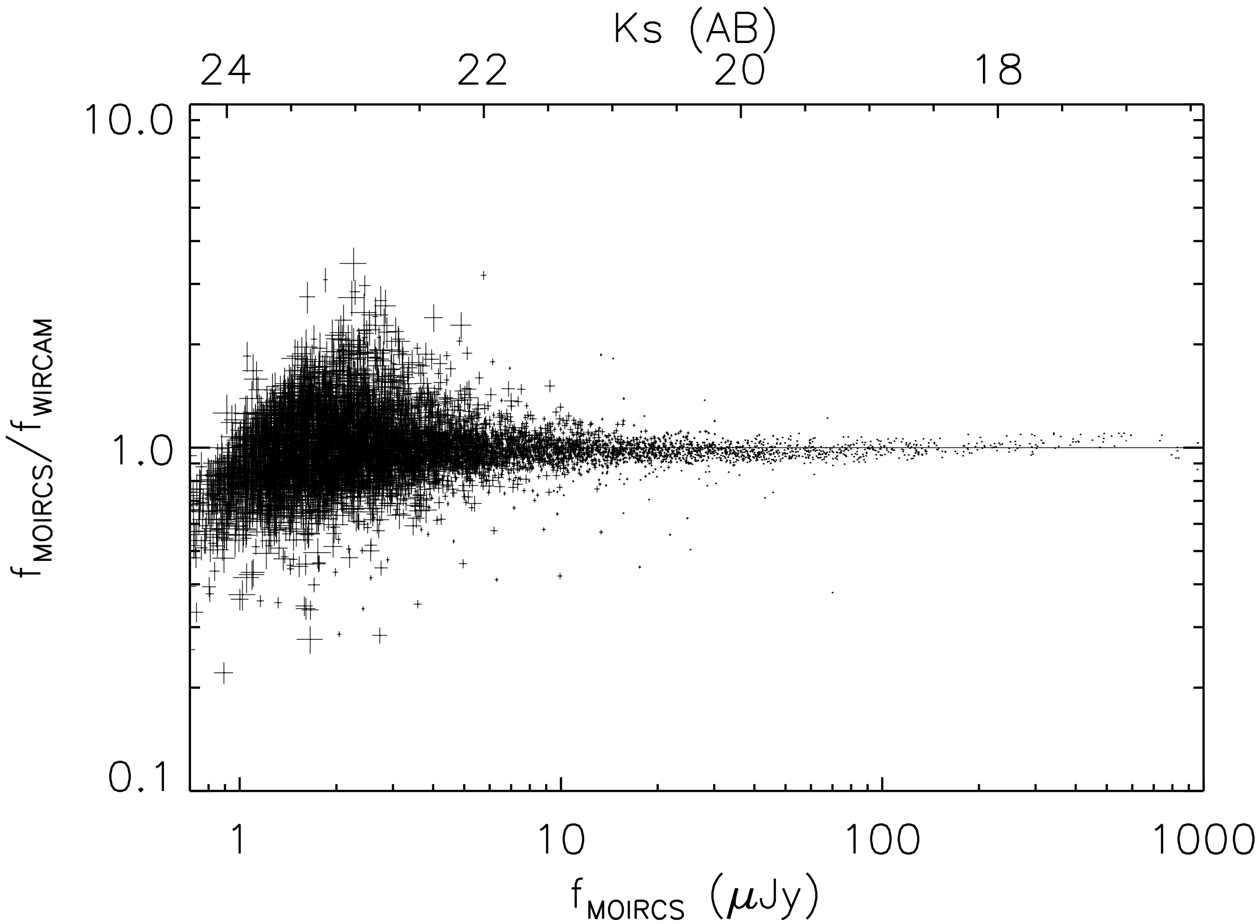

Fig. 7.— Comparison between the K_s fluxes in the WIRCAM and MOIRCS images in the GOODS-N. The WIRCAM image was calibrated with 2MASS and the MOIRCS image was calibrated with UKIRT Faint Standards. Only 10 σ objects in both images with major axes less than $1''.5$ are included here. Error bars for both fluxes and flux ratios derived from SExtractor errors are plotted for all data points but are invisible at $\gtrsim$ 10 μJy. The flux ratios are flat over a large magnitude range and in a wide field of view of $18' \times 12'$. The rms scatter at $>$ 20 μJy is 0.042 mag.

source positions in a reduced image and in the input catalog can be as good as 1/10 the pixel size (Fig. 8b) or $0''.02$ (Fig. 8c) over a large area.

It is useful to compare the image quality in a reduced image and that in the raw images. To do this, an isolated bright star (but not saturated) was selected from the WIRCAM J band image in the GOODS-N. Its PSF FWHM was measured in each individual exposure before the image was warped, and also measured in the final stacked image. From Fig. 9, it can be seen that there is a slight increase in the final FWHM comparing to the raw FWHM. In this particular case, the increase in the image FWHM is $\sim$ 14%, from $0''.77$ to $0''.88$. Analyses of the warped but unstacked images show that the degrade in image quality is entirely caused by the IDL bilinear interpolation

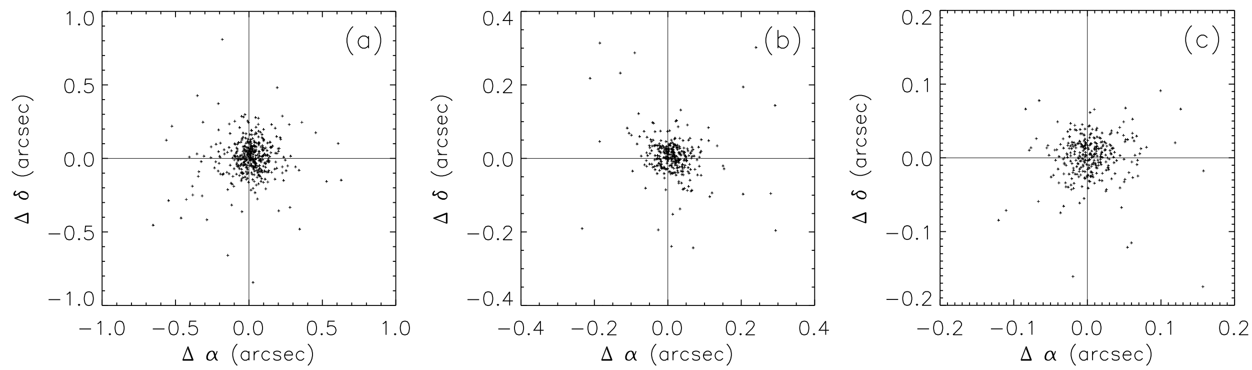

Fig. 8.— Comparisons between source positions in SIMPLE reduced images and in various catalogs. (a) WIRCAM J image in the GOODS-N vs. the SDSS catalog. The field of view is approximately 0.5 degree. (b) WIRCAM J image in the GOODS-N vs. the GOODS-N ACS catalog (Giavalisco et al. 2004). The coverage of the GOODS-N catalog is approximately $12' \times 18'$. (c) MOIRCS K_s image in the GOODS-N vs. the GOODS-N ACS catalogs. In all the reductions, the astrometric catalog is made by combining the SDSS and the ACS catalogs. In all the comparisons, only sources brighter than 22th AB mag. are included. In the comparisons to the ACS catalog where source sizes are better measured, only the top 30% most compact sources are included. The $0''.38$ offset between the ACS catalog and the radio frame is corrected here. After excluding the most obvious outliers, the rms scatters in the scalar offsets in (a), (b), and (c) are 80, 33, and 19 milli-arcsec, respectively. The offset vectors do no appear to be functions of locations in all three cases.

in the image warping stage, and the errors in absolute and relative astrometry are negligible here. In this particular example, changing the interpolation to bicubic only slightly improves the FWHM from $0''.88$ to $0''.85$. This is a fundamental limit of resampling images that are very close to being Nyquist sampled (the pixel scale of WIRCAM is $0''.3$) and is a weakness of SIMPLE that critically needs improvement. To improve this aspect of SIMPLE, the drizzle method or other interpolation methods are needed and this will be addressed in the future versions of SIMPLE.

11. Summary

SIMPLE is an IDL based data reduction environment for wide-field near-infrared images from mosaic cameras. It is available on the web and the current distributions are optimized for two mosaic cameras — CFHT WIRCAM and Subaru MOIRCS. With properly dithered images, SIMPLE can provide extremely well flattened images with iterative night-sky flats and can correct for optical distortion without relying on any external information. However, SIMPLE requires external catalogs for the calibrations of absolute astrometry and photometry. Examples of SIMPLE reductions show that SIMPLE can achieve excellent photometry with systematic errors of $\lesssim 0.03$ mag and excellent astrometry with errors as small as $0''.02$ rms relative to the input catalog. However,

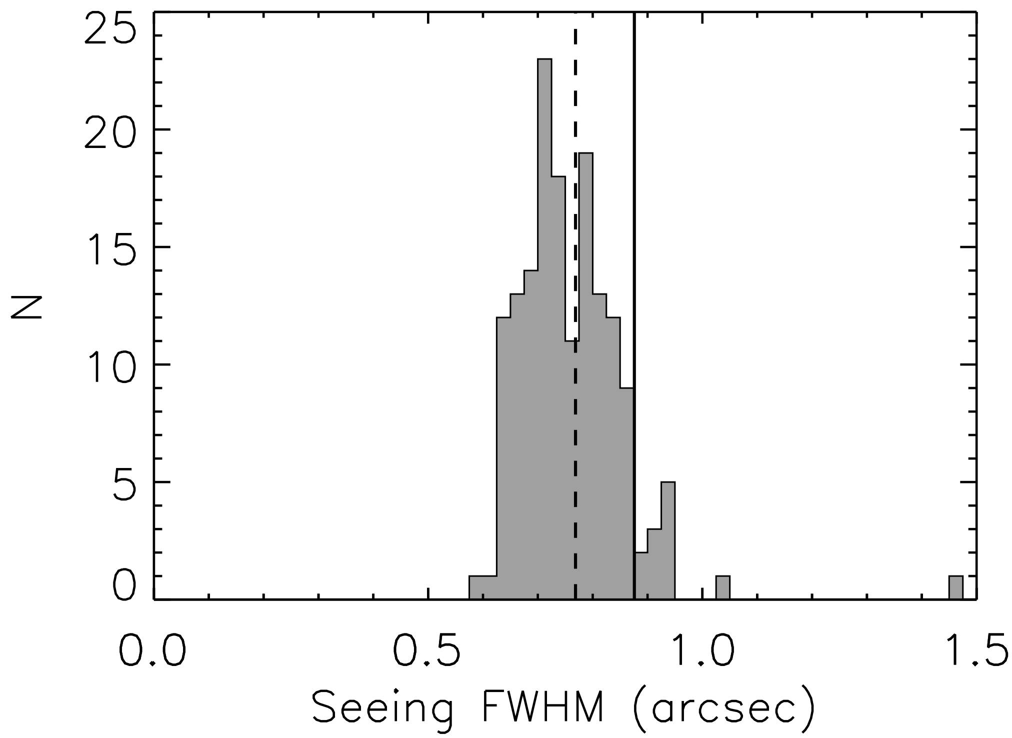

Fig. 9.— Comparison between the raw image quality and the image quality in the final stacked mosaic. The histogram shows the FWHM of a bright, isolated star in 158 170 sec WIRCAM J band exposures. The vertical solid line is the FWHM measured in the final mosaic, which is $0\farcs88$. The vertical dashed line is the mean of the 158 seeing measurements, which is $0\farcs77$. The difference between the two vertical lines is $0\farcs11$ (14%). This increase in image FWHM is caused by the adopted bilinear interpolation.

because of the adopted interpolation method, SIMPLE increases the image FWHM by $\sim 10\%$ to 20% on images that are close to being Nyquist sampled. This is the area where improvements are critically needed. Other possible future improvements are the inclusion of higher order terms in the polynomial distortion functions and in their derivatives to correct for the large distortions of large optical cameras, and the implementation of drizzle to improve image quality and to decrease noise correlation between pixels.

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