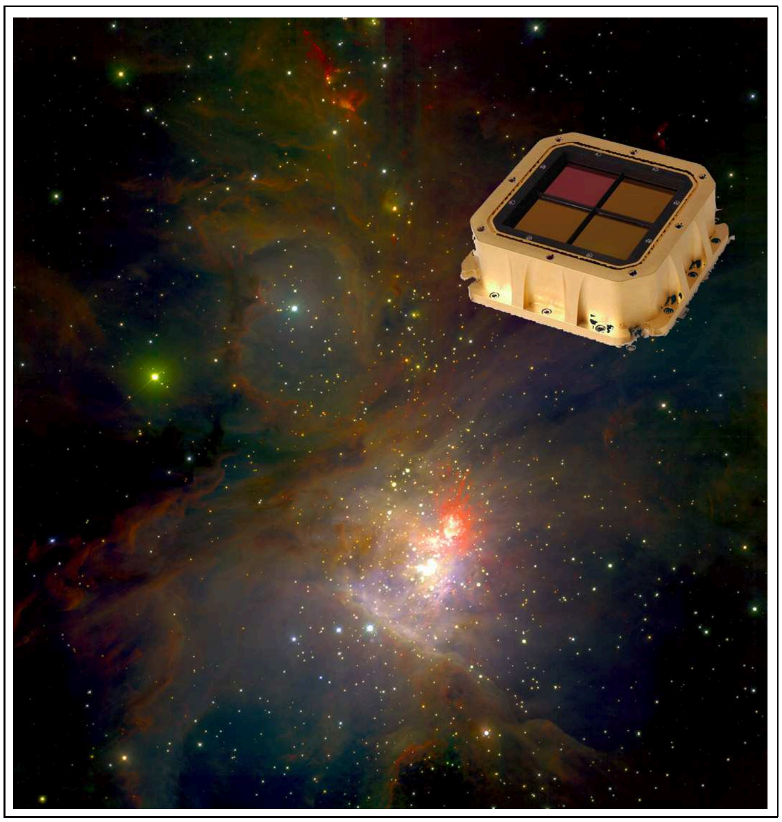
WIRCam data reduction @ Terapix
*v*1.0



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COVER ILLUSTRATION: WIRCam detectors (Gerry Lupino, GL Scientific) on the Orion Nebula (©CFHT/TERAPIX).

Contents

1 Introduction

WIRCam is the newest wide-field mosaic camera available at CFHT. Table 1 summarizes the characteristics[1] of the detector.

WIRCam implements dithering and optional micro-dithering of its images. The dithering observation strategy, adopted to optimize sky-subtraction procedure, consists of observing the same field with small offsets around a central position. In the micro-dithering mode successive images are offset by half a pixel. The WIRCam pixel scale is 0.3”/*pixel*, so that under good seeing conditions ($< 0.6''$) images can be undersampled. A composite image with finer sampling (0.15”) can be constructed from the set of micro-dithered images, using a number of data processing techniques.

The CFHT pipeline provides users with pre-processed images, i.e., de-biased, flat-fielded and sky-subtracted. WIRCam images are stored as multi-extension FITS (MEF) files containing four extensions (one per detector). Each extension may contain a cube of images (if multiple exposures are taken at each telescope position or/and micro-dithered), or one single image (if not). The data are stored as 16-bit signed integers, giving a minimum size for a WIRCam file of slightly above 32 MB. A Preliminary astrometric solution and photometric zero-point are also computed at this stage[2].

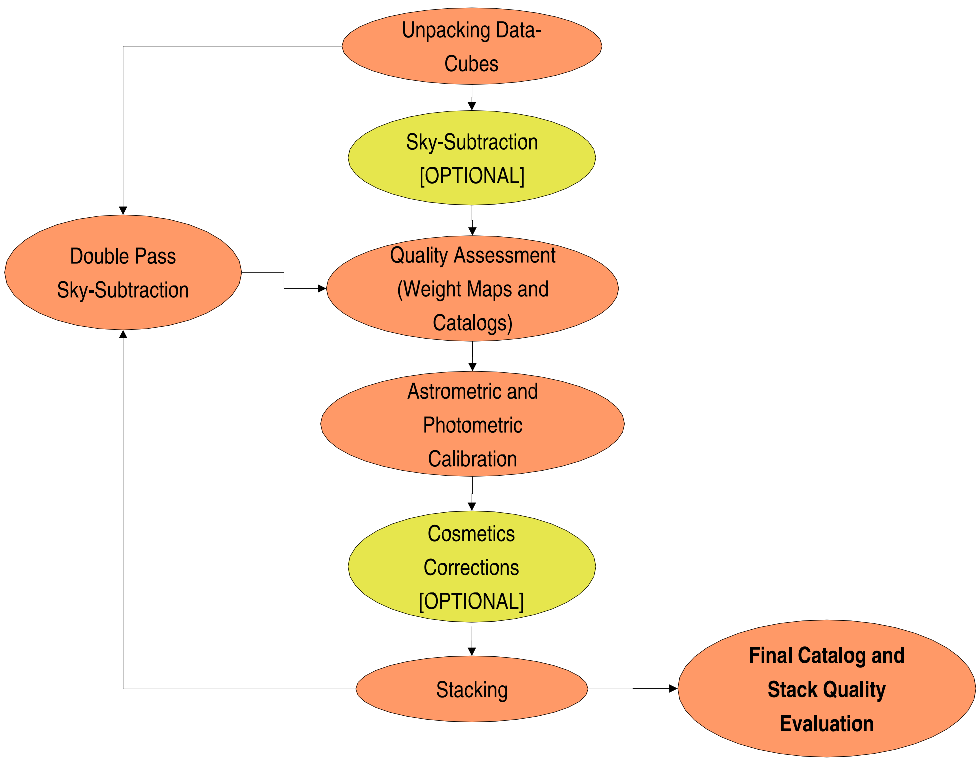

Figure 1: the TERAPIX-WIRCam Data Flow.

Terapix has developed tools for the reduction of the WIRCam data performing the following

[1]Technical details about detectors and general instrument performances can be found at http://www.cfht.hawaii.edu/Instruments/Imaging/WIRCam/ . General filters description is available at http://www.cfht.hawaii.edu/Instruments/Filters/wircam.html

[2]See for more details http://www.cfht.hawaii.edu/Instruments/Imaging/WIRCam/WIRCamPreprocessing.html

steps (summarized in Figure 1):

- splitting image cubes, if necessary (see section 2),
- optional sky subtraction (see section 3),
- quality assessment and production of weight maps (see section 4),
- precise astrometric and photometric calibrations (see section 5),
- double pass sky subtraction (see section 6),
- optional cosmetic corrections (correction of ”guiding trails” for example, see section 7),
- image stacking (see sections 8),
- delivery of catalogs and final quality assessment (see section 9).

Some additional tools and solutions were prepared for the first test phase of data processing:

- a solution for the relative calibration of detectors, using SCAMP[3] (see appendix A).

This document describes the WIRCam processing steps carried out at TERAPIX as on May 2007.

Number of detectors	$4 = 2x2$
Pixel dimension	18 *microns*
Pixel size	0.3 *arcsec*/*pixel*
Detector size	$2048x2048$ *pixels*
Camera field of view	21.5 *arcminute*
Effective Area	~ 419 *arcminute*^{2}
Field distortion	$< 0.8\%$ in the corners
Gaps between detectors	45 *arcsec*
Available filters	from 1000*nm* to 2200*nm*

Table 1: main characteristics of the WIRCam mosaic.

2 Splitting image cubes

Because of the large number of background photons at longer wavelengths, near-infrared detectors saturate faster than optical detectors: to avoid this effect, the typical exposure time is shortened and the number of exposures around the same coordinates is increased. In addition, infrared observations are often performed using dithering or micro-dithering strategy.

At, CFHT decided to store WIRCam FITS images as data cubes to reduce the number of files in their archive. Consequently, all images in a cube share the same header.

In general TERAPIX software tools do not accept data formatted in image cubes. After some tests, in particular concerning the computation of the astrometric solution and the stack production (see for details section 5.1), it became clear that there was no advantage for TERAPIX in keeping the pixels in data-cubes. In fact, there is no three-dimensional information in CFHT data-cubes. Every slice of a cube is actually an image with changing seeing, sky features, photometric quality

[3]http://terapix.iap.fr/soft/scamp

and zero-points: quality assessment has to be performed before any slice medianing or combining. In addition, in the case of micro-dithered exposures, the PSF is affected by pixel-to-pixel combinations, more or less depending on image seeing: the TERAPIX software tools can perform astrometry precisely enough to resample and stack images with half a pixel of displacement.

A C program has been developed to split the cubes, using Emmanuel Bertin FITS-LDAC library. MissFITS[4] works with MEF or single extension cubes of images: asking for an INPUTFILE.FITS on the commad line, it splits an image cube with NAXIS=3 and NAXIS3=N in N images with NAXIS=2.

All processing steps thereafter use these "unpacked" images.

3 Sky subtraction

CFHT provides sky-subtracted images. Until now, in some cases, in particular very deep observation programs, it was needed to redo this processing step.

`subsky.pl` is an automatic procedure to carry out sky subtraction for infrared dithered observations. In order to minimize telescope overheads, dithering consists of observing the object field at fixed offsets around a central position. A median pixel to pixel combine provides an estimation of sky variations, if correct masking and normalization are applied.

Further complications arise when images belonging to the same cube are microdithered. In this case cosmetic defects must be masked in order to avoid to enhance them in the sky frame. In particular, trails around bright stars used for guiding need to be masked.

In general, considering the typical exposure time of WIRCam exposures, we use only images within a thirty minute time window around the image we want to subtract.

Here are the steps carried out by the `subsky.pl` procedure.

1. SExtractor[5] produces a "checkimage" of type "OBJECTS" that WeightWatcher[6] transforms into a weight image, having 0 were objects are and 1 were objects are not.

2. If the option is active, a one-dimensional fit of the background is produced using SExtractor (masking objects with masks produced in step 1) in x and y directions: peaks in the background are detected using SExtractor again and masked using WeightWatcher. This option can be activated when crosstalk due to the guide star (see Section 7 for more details) is particularly evident and can affect the median for sky-frame production.

3. A number of images (which can be specified in the command line) is median-combined to create the sky image: an even number n of images is recommended, in order to have the same number of images acquired before and after the image we want to sky-subtract. The image itself is not used in the sky combine. Obviously if the image is the first or the last of the list, all images used for the sky combine are acquired after or before it. Note that this step produces an image of the sky, relative to each extension in each image, not a MEF.

4. The sky image is subtracted to the image and extensions are joined: the final result is a sky-subtracted MEF image.

The command line must contain the list of images to be sky-subtracted; the options are

- the number of extensions (`--n-exten -N`, if images are not MEF `--n-exten 1`),

- the number of images to compute the sky frame (`--n-images -n`),

[4]http://terapix.iap.fr/soft/missfits
[5]http://terapix.iap.fr/soft/sextractor
[6]http://terapix.iap.fr/soft/weightwatcher

- the bad pixel mask (if it exists), to be used as a weight image in detecting objects for mask (`--mask -M`),
- the input mask suffix, if an individual bad pixel mask had been produced (`--inweight-suffix`),
- the output mask suffix (`--outweight-suffix`),
- the detection threshold for object masking (`--threshold`),
- the activation of guiding trails masking (`--guide-on`),
- the number of processors available for the parallelization of the mask production (`--n-thread -T`).

Masks creation is optional, and can be deactivated using `--disable-mask`. For debugging reasons, the user may prefer to produce all the masks before applying any sky subtraction. In this case, sky subtraction can be skipped using the option `--disable-sky`.

The option `--verbose` when selected forces the TERAPIX software used in the procedure to run using VERBOSE_TYPE NORMAL. Otherwise the VERBOSE_TYPE QUIET is used.

The option `--mail (your e-mail-address)` when selected send an e-mail to the specified address when the processing ends.

Object masking is an essential step in sky frame production. If not masked, objects can affect the sky estimation, producing an overestimation of the background and a consequent underestimation of the flux in the subtracted image.

4 Quality assessment for input images

The quality assessment step is performed using QUALITYFITS. During this step general properties of images are analyzed: seeing, background, PSF quality are estimated. Catalogs for astrometric and photometric calibrations are extracted and weight maps generated for every image. Due to the detector characteristics some differences arise with respect to the configuration parameters used for MegaCam data. In particular:

- bad pixels identification is made using an ad-hoc SExtractor filter (built using EyE[7]), available in the `config` directory of QUALITYFITS as `wircam.ret`
- a .reg file is also introduced in building weight maps, masking edge zones strongly affected by a large number of bad pixels
- SExtractor parameters are adjusted to improve the detection reliability, threshold for detection is 2σ above the background, and the parameter INTERP_TYPE NONE is used to eliminate spurious detections in zero weighted zones (the user can modify those parameters in any time using the configuration file of QUALITYFITS)
- as the WIRCam pixel-scale is $0.30''$, when the seeing is good ($\sim 0.6''$), sources can be undersampled, PSFEx PSF_NSUPER parameter is set to 64, meaning that the 64 brightest pixels in the objects are used to derive a superresolved PSF model.

In addition, for WIRCam observations, the guiding strategy produces holes in the observed field corresponding to bright stars used for guiding. Hence, we introduce the possibility of flagging and weighting as zero the guiding holes in the weight map production step: as guiding stars are not the same for every pointing, the weighted coaddition can take this problem into account and leaves no holes in the final image.

[7] http://terapix.iap.fr/soft/eye

5 Astrometric and photometric calibration

5.1 Astrometry.

A precise astrometric calibration is required for a proper stacking of images.

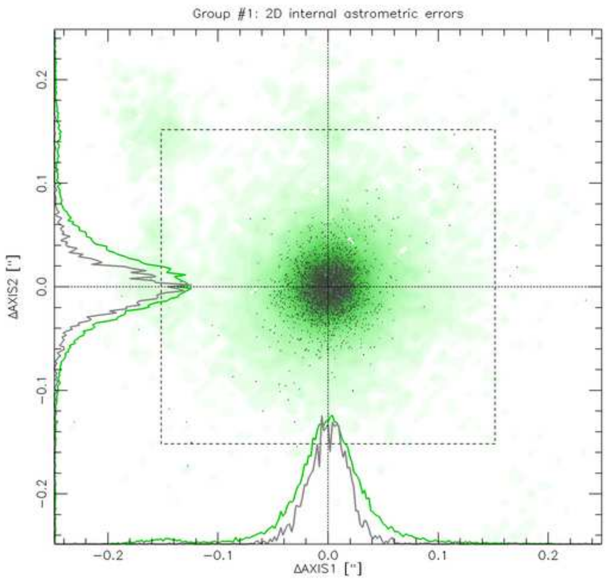

Figure 2: an example of two-dimensional histogram of astrometric residuals in a micro-dithered set of images.

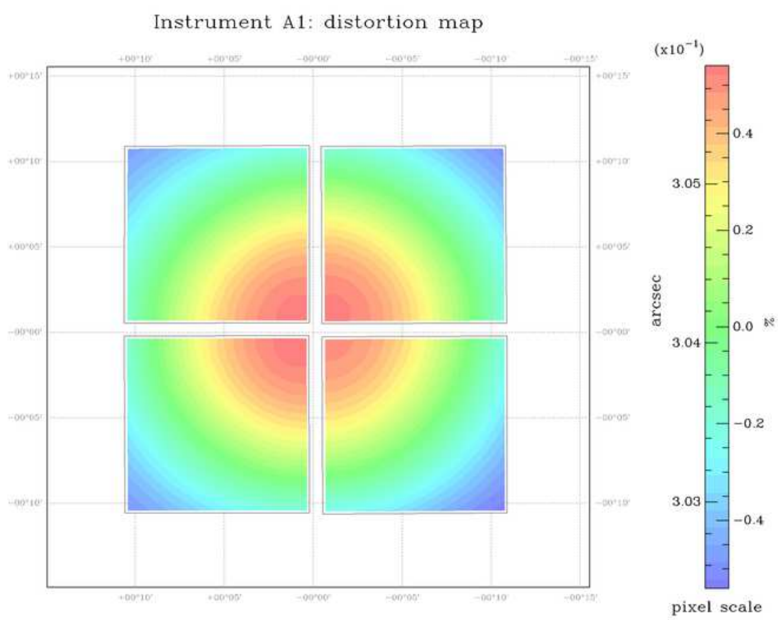

Figure 3: computed pixel scale distortion for WIRCam.

To perform a correct and general resampling of images and avoid the problem of inaccurate offsets, no difference is made between micro-dithered or no-micro-dithered images, this is why (as stressed in section 4), identifying spurious detections is so important. In fact, the position of bad pixels and defects on the detector remains constant. Because of small offsets between real objects in the case of micro-dithering, those spurious detections are easily matched by automatic procedures and the astrometric solution can be degraded. This effect is well represented in Figure 2, where three clouds of matched low signal-to-noise objects are present at half pixel from the plot center.

The astrometric calibration is performed using SCAMP. A stellar astrometric field was provided by QSO CFHT team. From this field we produced a model of the WIRCam focal plane. The 2MASS catalog is used as astrometric reference and a fourth degree polynomial solution is computed. Typical values for the pairwise residuals of the astrometric solution between overlapping detections go from $\sim 30 mas\ rms$, for a few tens of exposures, to $\sim 90 mas\ rms$, for several thousands of exposures. Typical values of residuals with respect to reference catalog are $\sim 130 mas\ rms$. WIRCam can be considered an astrometrically stable instrument. Figure 3 represents the distortion calculated for the WIRCam focal plane.

5.2 Photometry.

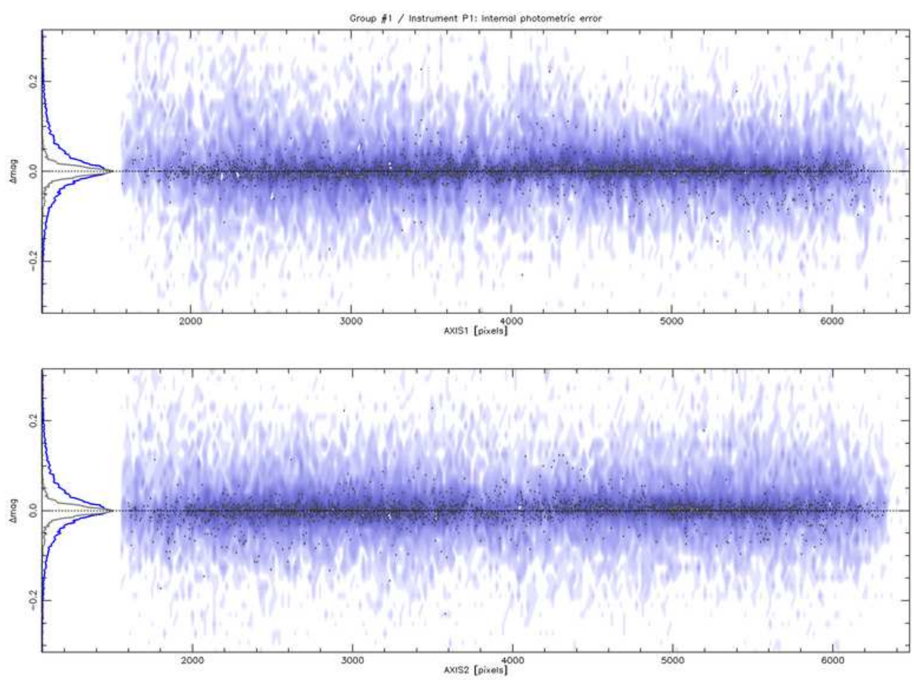

Figure 4: Photometric calibration repeatability.

SCAMP does not perform absolute photometric calibration with respect to a catalog, but if an image is labeled as photometric, SCAMP scales all other images to the predefined output zero-point using the photometric image as a reference (see [1] for details). For 2MASS-like WIRCam filters (H, J, Ks), CFHT provides a photometric calibration on 2MASS-Vega system: the zero-point is provided for every extension and every image in a specific header keyword. All images with their own 2MASS-Vega zero-points can be considered and labeled as photometric except those having no zero-point keyword. If short ($< 10 sec$) and long exposures are available, only short exposures are labeled as photometric. This is because bright 2MASS objects are often saturated on long exposures: their photometric measurements are not reliable for a photometric calibration.

If none of the images have photometric zeropoint a calibration is possible using the procedure described in appendix A.

Photometric repeatability has been tested comparing two stacks covering the same sky region, having a total exposure time of $\sim 1600 sec$. The result of this comparison is represented in Figure 4. The pairwise residuals for high signal-to-noise-ratio objects is $\sim 0.025 mag\ rms$.

6 Double pass sky subtraction

In infrared observations the background is affected by faint objects often undetectable in single images but present if stacks are deep enough. When the background is computed in the single image before combine, it is in general slightly overestimated and can affect final object magnitudes that are consequently underestimated. Therefore, it is necessary to build a stack from which deeper masks will be derived for a better estimation of the background.

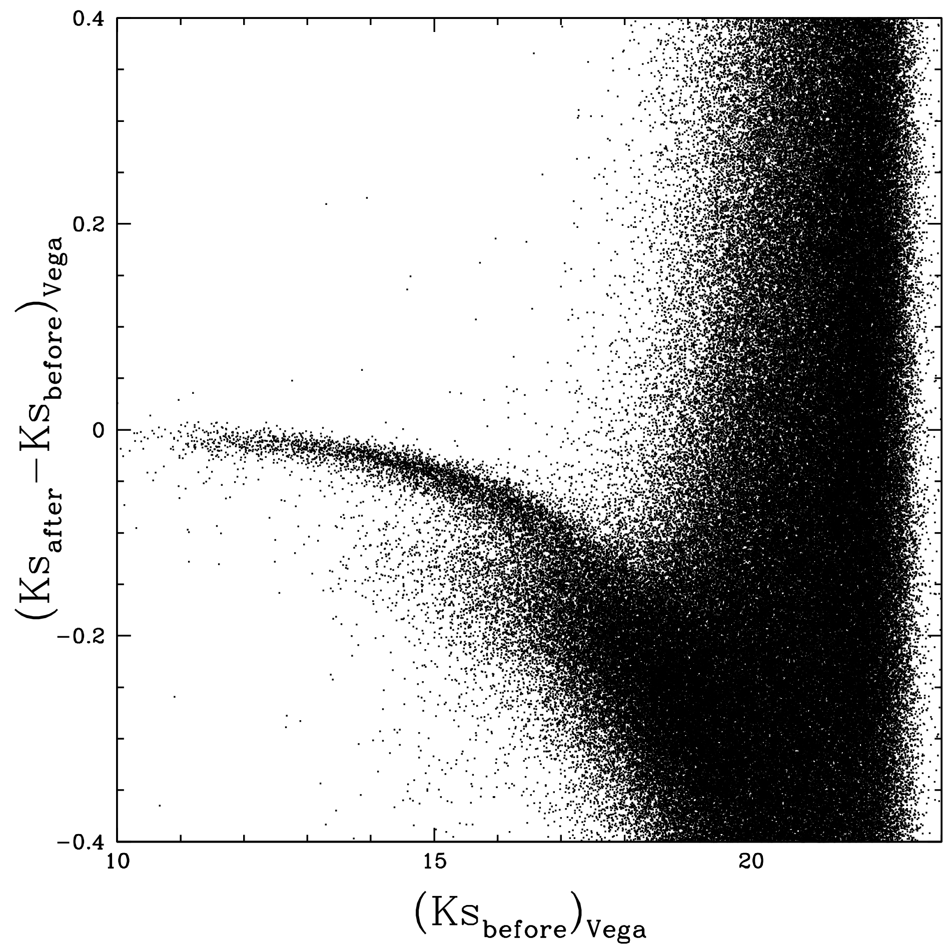

Figure 5: comparison between Ks magnitude measured without object masking (Ks_{before}) and with object masking (Ks_{after}) in the second pass mode. The wings of objects not masked out during the computation of the background are partially "absorbed". This produces an overestimation of magnitudes which depends on the intensity and the profile shape of the object itself.

In Figure 5 the difference between magnitudes in the masked and unmasked subtraction is plotted versus unmasked magnitude, for Ks band.

The procedure described in section 3 is runned in a second pass mode (`--pass2` option). In this mode masks are produced from a preliminary stack. A reference stack and its weight need to be specified using `--image` or `-I` for the stack and `--weight` or `-W` for its weight map.

Here the steps performed in this second sky subtraction.

1. A flag image is created using SExtractor on the stacked image, having 1 where objects are and 0 elsewhere. The detection is weighted and performed with a low threshold, no deblending or cleaning is applied: we are not interested in detect astronomical objects but sources which can perturb the background calculation.

2. The flag image is re-projected on every image using SWarp[8], following the astrometric solution computed by SCAMP and used for the combine of the first stack.

3. For every image a new weight map is produced, using WeightWatcher, having zeroes wherever pixels are flagged.

4. As for the first subtraction a specified number of images is combined (median) to create the sky image.

5. The sky image is subtracted from the image and extensions are joined: the final result is a sky-subtracted MEF image.

7 Cosmetic corrections

The `subguide.pl` procedure removes guiding trails from images. Guiding trails are remanence effects with roughly constant profile, occasionally affecting stars used to guide exposures. They can reach a surface brightness of $\sim 20 mag/arcsec^2$ in the Ks band and $\sim 21 mag/arcsec^2$ in the J band.

Here are the steps performed by the `subguide.pl` procedure.

1. SExtractor produces a "checkimage"of type "OBJECTS" that WeightWatcher transforms into a weight image, having 0 were objects are and 1 elsewhere.

2. A monodimensional fit of the background is produced with SExtractor (masking objects with masks produced in step 1) in the x and y directions (Step 2 in Figure 6).

3. Peaks in the background are detected using SExtractor and a checkimage OBJECTS is produced (Step 3 in Figure 6).

4. The checkimages in x and y are combined using SWarp in a "guiding trails" image (Step 4 in Figure 6).

5. The "guiding trails" image is subtracted from the image (Step 5 in Figure 6).

On the command line the list of images to be subtracted is an argument; the options are

- the number of extensions (`--n-exten -N`, with N=1 if images are not MEF),

- the bad pixel mask (if it exists), used as a weight image in the building mask process (`--mask -M`).

Step 1, the mask production, is roughly parallelized: the option `--n-thread -T` fixes the number of processors we can use. Mask production is optional, and can be deactivated using `--disable-mask`. If mask production is switched off external masks for computing the background are specified with the option `--inweight-suffix`.

[8] http://terapix.iap.fr/soft/swarp

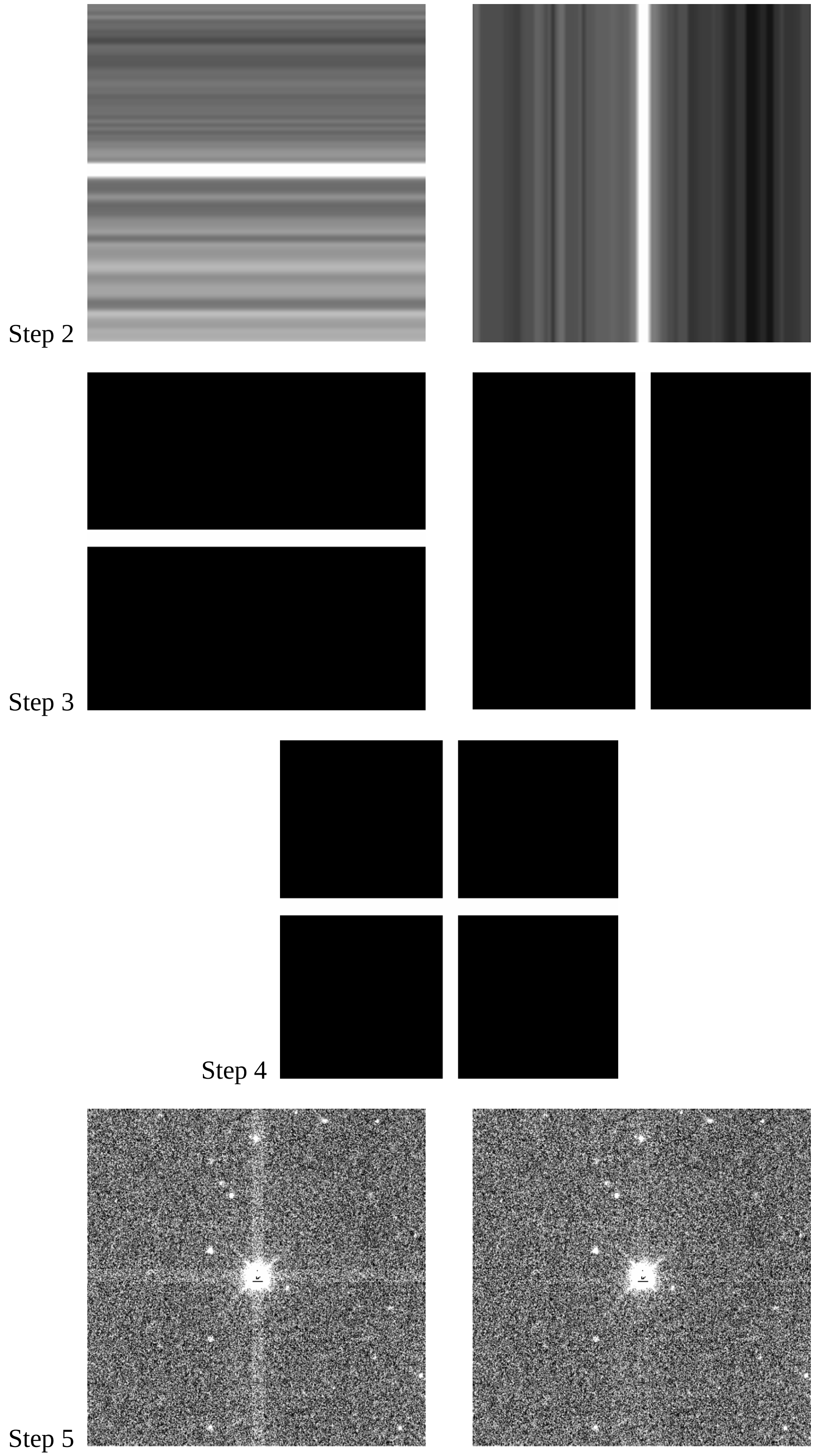

Figure 6: Steps of ’guiding trails’ correction.

8 Stacking images

With ”clean” individual exposures in hand astrometric and photometric calibration needs to be redone. All the steps described in section 4 and 5 are now performed again on the double pass sky-subtracted images.

Images are resampled and combined using SWarp in the context of the last astrometric and photometric calibration. We use the LANCZOS2 resampling function of SWarp. Higher orders of Lanczos function provide generally better resampling, but in the WIRCam case we decided to use LANCZOS2 because of the huge pixel scale (0.3″) compared to the minimum seeing one can obtain at CFHT (0.5″). Data may be undersampled in case of very good seeing and resampling with Lanczos function of higher order may generate extended ripples around bright stars (see [2] for more details).

In practice, seeing is often worse than 0.5″, but, as one can see in Figure 7 (top), for good seeing LANCZOS3 or LANCZOS4 can produce artifacts around bright stars. In addition, using LANCZOS3 or LANCZOS4 functions to resample images strongly affected by bad pixels (an example is represented in Figure 7 (down)) produces extended artifacts.

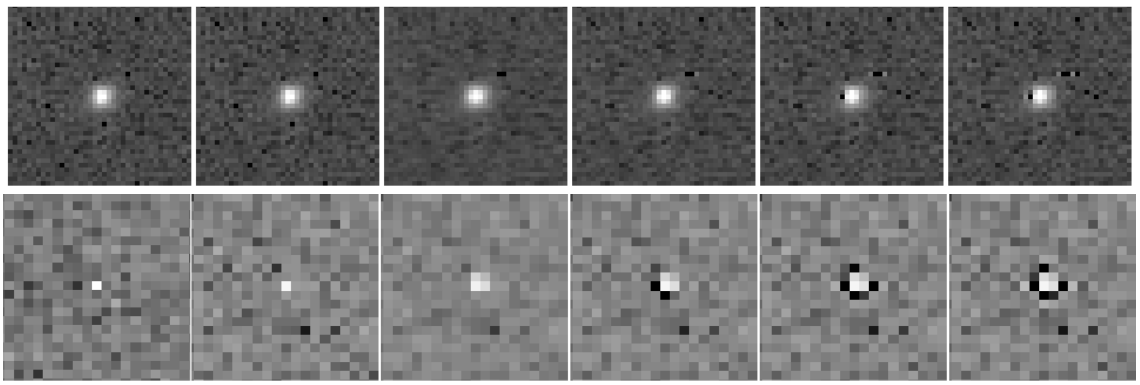

Figure 7: (top) from right to left: a star having a FWHM of 0.61*arcsec* (represented in the first image) has been resampled with NEAREST, BILINEAR, LANCZOS2, LANCZOS3, LANCZOS4 functions. (down) the same for a bad pixel, an example of high undersampled source.

9 Final data products

Among other things, the quality assessment stage yields seeing and background distributions, as well as a preliminary star/galaxy separation. All these results are presented in an HTML page generated by qualityFITS. A catalog containing basic object parameters is extracted and used for quality assessment. A .reg mask made from the final stack can be used in qualityFITS to flag pixels and cataloged objects . Sometimes negative crosstalk residuals are still present in the final stack: they can be flagged by producing a negative image and detecting 'objects' on it. If observations have been done through several filters, a chi2 combined image (see [5]) can also be provided with catalogs containing magnitudes in each filter for all objects.

10 Example of a data processing session

10.1 Splitting the cubes

See section 2 for details.

```
mkdir cubes

mkdir images
```

```
cd cubes

missfits -c missfits.conf -OUTFILE_TYPE SLICE -SLICE_SUFFIX _\%02d.fits
-SAVE_TYPE BACKUP <image>.fits

cd ../images
```

10.2 Subtracting the sky

See section 3 for details.

```
subsky.pl <list-of-files> -N 4 -n 25 --outweight-suffix <suffix>.fits
-M <badpix-mask> -T 4
```

10.3 Quality assessment

See section 4 for details.

```
qualityFITS -c <config-file>.rc <list-of-files> -F <flat> -P <region>
-M <badpix-mask>
```

10.4 Astrometry and photometry

See section 5 for details.

```
cd ..

mkdir scamp

cd scamp

ln -s ../images/*/qualityFITS/*.ldac .

scamp *.ldac -c scamp.conf -MOSAIC_TYPE SAME_CRVAL -AHEADER_GLOBAL wircam.ahead
-SOLVE_ASTROM Y -SOLVE_PHOTOM Y -MAGZERO_KEY PHOT_C0 -CHECKPLOT_DEV PNG
-CHECKPLOT_ANTIALIAS Y
```

10.5 Stacking

See section 8 for details.

```
cd ..

mkdir swarp

cd swarp

ln -s ../scamp/*.head .

ln -s ../images/*/qualityFITS/*_weight.fits .

ln -s ../images/*.fits .
```

```
swarp *.fits -c /home/nis/marmo/Wircam/config_files/swarp.conf
-IMAGEOUT_NAME <out1_stack_name> -WEIGHTOUT_NAME <out1_weight_name>
-RESAMPLING_TYPE <resampling_type> -BACK_SIZE <back_size> -WEIGHT_SUFFIX _weight.fits
-WEIGHT_IMAGE "" -COMBINE_TYPE <combine_type> -COPY_KEYWORDS OBJECT,FILTER
-WEIGHT_TYPE MAP_WEIGHT
```

10.6 Double pass sky subtraction

See sections 3 for details.

On no-sky-subtracted images

```
subsky.pl <list-of-files> -N 4 -n 23 --outweight-suffix <suffix>.fits
-I <out1_stack_name> -W <out1_weight_name> -T 4
```

10.7 Redoing astrometry and photometry

```
cd ../scamp

scamp *.ldac -c scamp.conf -MOSAIC_TYPE SAME_CRVAL -AHEADER_GLOBAL wircam.ahead
-SOLVE_ASTROM Y -SOLVE_PHOTOM Y -MAGZERO_KEY PHOT_C0 -CHECKPLOT_DEV PNG
-CHECKPLOT_ANTIALIAS Y
```

10.8 Final products

Optional flagging of negative noise

```
swarp <out2_stack_name> -c swarp.conf -IMAGEOUT_NAME inv_<out2_stack_name>
-WEIGHTOUT_NAME inv_<out2_stack_name>.weight.fits -RESAMPLE N
-COMBINE_TYPE MEDIAN -COPY_KEYWORDS OBJECT,FILTER,MAGZEROP -WEIGHT_TYPE NONE
-FSCALE_KEYWORD NONE -FSCALE_DEFAULT -1. -SUBTRACT_BACK N

sex inv_<out2_stack_name> -WEIGHT_IMAGE <out2_weight_name> -c qualityFITS.sex
-CATALOG_TYPE NONE -CHECKIMAGE_TYPE OBJECTS -CHECKIMAGE_NAME invob.fits
-PARAMETERS_NAME none.param -STARNNW_NAME qualityFITS.nnw -WEIGHT_TYPE MAP_WEIGHT
-DETECT_MINAREA 3 -DETECT_THRESH 1.5 -ANALYSIS_THRESH 1.5 -MAG_ZEROPOINT 30.
-INTERP_TYPE NONE -FILTER_NAME gauss_2.5_5x5.conv

ww -c ww.conf -WEIGHT_NAMES invob.fits -WEIGHT_MIN -0.5 -WEIGHT_MAX 1.e-15
-FLAG_NAMES '' -WEIGHT_OUTFLAGS 1 -POLY_NAMES '' -OUTFLAG_NAME crosstalk.fits
```

Quality assessment

```
qualityFITS -c Wircam2pass.rc
<out2_stack_name> -W <out2_weight_name> -P <final_polygons> -M crosstalk.fits
-2 --scamp --logfile qFITS.log -vv
```

A Appendix. Relative photometric calibration

During the period of software testing and development a unique photometric zero-point was provided from CFHT for the four detectors. Nevertheless, this solution was not satisfactory: the photometric calibration performed by SCAMP results in a constant shift of the photometric zero point for each MEF:

If photometrically calibrated images are available, a solution is to split MEF images into single extension images and perform the photometric calibration (keeping the astrometric solution previously computed) on each extension separately, labeling the calibrated images as photometric.

To rescale the fluxes, SCAMP matches detection made in overlapping images between them: the accuracy of the solution depends on the number of matched objects. Hence, zeropoint differences can be better computed if the same objects are detected on different detectors: it means that the dithering must be not too small. On the other hand, reference image has to be deep enough to contain the same magnitude range with respect to the images we want to calibrate, and need to cover all the field covered by our images.

In particular, 2MASS images are available on-line[9]. They are calibrated in Vega system. Unfortunately, 2MASS images presents both disadvantages we described above: only very bright objects are presents on them, in addition they have little zones of superposition. The solution cannot be always optimal.

B Appendix. Vega to AB magnitudes transformations

2MASS (from [3])

$$J_{Vega} = J_{AB} - 0.89 \quad (1)$$
$$H_{Vega} = H_{AB} - 1.37 \quad (2)$$
$$K_{sVega} = K_{sAB} - 1.84 \quad (3)$$

WFCAM (from [4])

$$Y_{Vega} = Y_{AB} - 0.634 \quad (4)$$
$$J_{Vega} = J_{AB} - 0.938 \quad (5)$$
$$H_{Vega} = H_{AB} - 1.379 \quad (6)$$
$$K_{Vega} = K_{AB} - 1.900 \quad (7)$$

WIRCam[10]

$$Y_{Vega} = Y_{AB} - 0.66 \quad (8)$$
$$J_{Vega} = J_{AB} - 0.96 \quad (9)$$
$$H_{Vega} = H_{AB} - 1.40 \quad (10)$$
$$K_{sVega} = K_{sAB} - 1.99 \quad (11)$$

Acknowledgments

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[9] http://irsa.ipac.caltech.edu/applications/2MASS/IM/
[10] http://www.cfht.hawaii.edu/Instruments/Imaging/WIRCam/quickinformation.html

References

[1] Bertin, E., SCAMP User's guide.

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[3] Finlator, K., Ivezić, Ž., Fan, X., Strauss, M. A., Knapp, G. R., Lupton, R. H., Gunn, J. E., Rockosi, C. M., Anderson, J. E., Csabai, I., Hennessy, G. S., Hindsley, R. B., McKay, T. A., Nichol, R. C., Schneider, D. P., Smith, J. A., York, D. G., the SDSS Collaboration, 2000, AJ, 120, 2615.

[4] Hewett, P. C., Warren, S. J., Leggett, S. K., Hodgkin, S. T., 2006 MNRAS, 367, 454.

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