

# Wide-field Infrared Survey Explorer



## Format Specifications for Pre-Flight Calibration Receivables

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WSDC D-I005

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## Revision History

<b>Date</b>	<b>Version</b>	<b>Author</b>	<b>Description</b>
December 6, 2007	1.0	Frank Masci	Initial Draft (darks and bad-pixel masks only)
February 25, 2008	2.0	Frank Masci	Completed all other instrumental calibration specs
March 6, 2008	2.1	Howard McCallon	Included specs for focal plane distortion calibration
March 13, 2008	2.2	Frank Masci	Included specs for Point Response Functions (PRFs)
April 23, 2008	2.3	Frank Masci	Changed filename formats to conform to WSDC standards
May 26, 2008	2.4	Frank Masci	Included PRF file naming and FPA-indexing convention
July 25, 2008	2.5	Frank Masci	Updated (suggested) gain and read-noise estimation methods
September 23, 2008	2.6	Frank Masci	Expanded some points re non-linearity; updated specs on cal masks; added cautionary note in section 1.4.
December 15, 2008	2.7	Frank Masci	- Updated methods for dark and responsivity estimation with uncertainties; - Refined gain and read-noise estimation methods.
May 17, 2009	2.8	Frank Masci	Simplified gain and read-noise estimation methods



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# 1 Introduction

## 1.1 Purpose and Scope

This document describes the required formats and content of pre-launch calibration products to support *instrumental frame calibration* at the WISE Science Data Center (WSDC). Suggested algorithms for generating these products, where applicable, are also given. We encourage the deliverer (presumably also the analyst) to optimize or even revise an algorithm, and let the WSDC know of the eventual algorithm used.

This is an evolving document as changes may occur or new products become available in the course of instrument characterization and testing.

## 1.2 Applicable Documents

- WISE Characterization and Calibration Plan (D-33753; version 1.3; Sept 2007)
- WISE Payload Electro-Optical (SDL) Characterization Plan (SDL/05-091; Mar 2007)
- WISE Digital Electronics Box (DEB) Processing description (SDL/06-070; Jan 2006):  
<http://web.ipac.caltech.edu/staff/roc/wise/docs/sdl06-070-.pdf> (**NEWER VERSION KNOWN TO EXIST!**)
- WISE Pixel Error Model (WSDC D-T001; version 1.0; Mar 2008):  
<http://web.ipac.caltech.edu/staff/fmasci/home/wise/WiseErrorModel.pdf>
- WSDC Functional Requirements Document (WSDC D-R001; version 2.0; Nov 2007):  
[http://web.ipac.caltech.edu/staff/roc/wise/docs/WSDC\\_Functional\\_Requirements\\_all.pdf](http://web.ipac.caltech.edu/staff/roc/wise/docs/WSDC_Functional_Requirements_all.pdf)
- Frame Pipeline Processing: Instrumental Calibration (internal working document):  
[http://web.ipac.caltech.edu/staff/fmasci/home/wise/ScanPL\\_instrumental\\_cal.pdf](http://web.ipac.caltech.edu/staff/fmasci/home/wise/ScanPL_instrumental_cal.pdf)
- Critical Design Review presentation: Instrumental Calibration (Jan 2008):  
[http://spider.ipac.caltech.edu/staff/fmasci/home/wise/InstruCal\\_CDRJan08.pdf](http://spider.ipac.caltech.edu/staff/fmasci/home/wise/InstruCal_CDRJan08.pdf)
- Some thoughts on the Droop Effect (Mar 2008):  
[http://web.ipac.caltech.edu/staff/fmasci/home/wise/Droop\\_question.pdf](http://web.ipac.caltech.edu/staff/fmasci/home/wise/Droop_question.pdf)
- Distortion Calibration and Code-V Modelling (June 2008):  
<http://web.ipac.caltech.edu/staff/fmasci/home/wise/codeVdist.html>

### 1.3 Acronyms

ADC	Analog-to-Digital Conversion
ADU	Analog Digital Unit
ASCII	American Standard Code for Information Interchange
BITPIX	Bits per Pixel
COV	Covariance
CR	Cosmic Ray
DC	Direct Current
DEB	Digital Electronics Box
DN	Data Number
FITS	Flexible Image Transport System
FOV	Field of View
FPA	Focal Plane Array
FPMA	Focal Plane Mount Assembly
FWHM	Full Width at Half Maximum
IOC	In-Orbit Checkout
IPAC	Infrared Processing and Analysis Center
IPC	Inter-Pixel Capacitance
LSB	Least Significant Bit
MAD	Median Absolute Deviation
PRF	Point Response Function
PSF	Point Spread Function
RN	Read Noise
SD	Standard Deviation
SDL	Space Dynamics Lab
SIP	Simple Imaging Polynomial
SNR	Signal to Noise Ratio
SUR	Sample-Up-the-Ramp
TBD	To Be Determined
TBR	To Be Resolved
WCS	World Coordinate System
WISE	Wide-field Infrared Survey Explorer
WSDC	WISE Science Data Center
WSDS	WISE Science Data System

### 1.4 Cautionary Note

The pixel numbering and ordering as represented in the FPA Mount Assemblies (FPMAs), and hence inherent in all calibration *image* products described in this document will not match that of the flight image data *after* it is re-oriented to get the proper sky representation at the WSDC. The necessary flips and rotations for the calibration images are not known at the time of writing. The plan is not to transform ground calibrations in automated operations prior to their application, but to transform them before they're placed in the calibration archive. This may involve some recursive process whereby the relationship between orientations in the FPMA, downlink, and desired WCS first needs to be worked out, then applied and the data reprocessed.

## 2 Dark Current/Offset Correction

- The SDL characterization plan describes a test to calibrate the dark current and its variation for each array. This is accomplished by taking repeated images of a *cold* extended source at a set of temperatures (minimum, nominal and maximum). The plan is to derive dark images (and corresponding uncertainties) at each temperature for the four bands.
- Pre-processing steps and *suggested* algorithm:
  - It is assumed that all raw data frames have gone through DEB processing (as will be done in-flight) to yield pixel values in effective “slope” units. This is not known at the time of writing. If the test data instead consists of full ramp samples per pixel, then they will first need to be collapsed into effective “slope” units using the same algorithm outlined in the DEB processing document. We advise using the default (nine) SUR multiplication coefficients for now, unless SDL have specified otherwise. If the data is from a band 4 array, remember to down-sample the data (if not already) by *adding* the “slope” signal in every four adjacent pixels and truncating the two least significant bits from the result. This operation is also described in the DEB processing document.
  - For each frame (in “slope” units), the next step involves subtracting off the electronic bias structure (DC offset) from each amplifier channel using the reference (border) pixels. The algorithm is described in Appendix I. The impact of this step on the final noise is still under discussion with the Project Office (contact: Amy Mainzer), and is not yet fully characterized. It is advised that darks be created with and without this step applied so that we can decide later whether it improves or degrades the final product. Also, this operation *may* introduce severe residual artifacts in bands 3 and 4 due to an uncharacterized electronic signature known as “banding”.
  - The next step involves optimally combining the “slope” image frames (versions with and without reference pixel bias subtraction) to create the dark products. Either of two methods can be used: simple un-weighted averaging with upper and lower sigma clipping (to reject outliers – see below), or a straight median. A median will give products with slightly higher uncertainty than averaging, however this is a small price to pay given its robustness against outliers. We recommend using a median. There will be enough data to still get a good SNR in the end. If the median is the method of choice, then a robust measure for its 1-sigma uncertainty can be estimated from either: (i) the sample Median Absolute Deviation (MAD):  $\sigma_m = 1.8577 * \text{median}\{|p_i - \text{median}\{p_i\}|\} / \sqrt{N}$ , where  $N$  is the number of values in a pixel stack, or (ii) the quantile difference:  $\sigma_m = 1.2533 * 0.5 * [q_{0.8413} - q_{0.1586}] / \sqrt{N}$ . The numerical factors account for the fact that the median is noisier than the mean, assuming the underlying population is Gaussian. If adamant on using trimmed averaging, we suggest the following procedure for a pixel stack: (i) compute a robust measure of the dispersion, e.g.,  $\sigma_d = 0.5 * [q_{0.8413} - q_{0.1586}]$ ; (ii) also compute the median  $m$ ; (iii) flag or omit outlying pixels with values  $p < m - n * \sigma_d$  and  $p > m + n * \sigma_d$  where  $n = 4$  or  $5$  (your choice); (iv) compute the mean  $\mu$  and standard deviation ( $SD$ ) of the remaining  $N$  samples in the stack. The mean is the calibration estimate and its uncertainty will be  $\sigma_\mu \sim SD / \sqrt{N}$ .
- The format for the dark images shall be in the Flexible Image Transport System (FITS). A sample FITS header is below. The angle brackets indicate information whose literal content depends on actual execution or generation circumstances.



```

SIMPLE = T / file does conform to FITS standard
BITPIX = -32 / number of bits per data pixel
NAXIS = 2 / number of data axes
NAXIS1 = <Num> / length of data axis 1
NAXIS2 = <Num> / length of data axis 2
BAND = <Num> / WISE band number (1, 2, 3 or 4)
TEMP = <x.x> / Array test temperature in Kelvin
VERSION = <x.x> / Version of calibration product
BUNIT = 'DN/SUR' / Units of image data
COMMENT WISE Dark calibration product, created <YYYY-MM-DD>
COMMENT by <Joe Astronomer> at <institute name>
COMMENT created from data set <ID of test data or description>

```

*Notes:*

- BITPIX = -32 refers to single precision floating point.
- For bands 1, 2 and 3, NAXIS1 = NAXIS2 = 1024. For band 4, NAXIS1 = NAXIS2 = 512. This implies the 4-pixel wide reference border in bands 1, 2 and 3, and 2 pixels wide in band 4 should be carried through the dark estimation process and retained in the final FITS products. It will be appropriately dealt with in processing at the WSDC.
- The VERSION keyword refers to the version number (e.g., v. 1.0 for initial version) of the calibration product. This is in case it is re-created using different inputs or methods later.
- BUNIT specifies the image data units. It is expected these will be the same as that of the raw data received from the spacecraft, i.e., proportional to DN / Sample-Up-the-Ramp (DN/SUR or effective slope) units. This measure is described in the DEB Processing document referenced in section 1.
- The *last* COMMENT line stores information on the data set from which the calibration product was created. This can be an ID for the test batch if available, or, the lab location and date where the test data was acquired.
- The corresponding uncertainty image should be stored in a separate FITS file. The header of this FITS image can be the same as above, except that a COMMENT field will need to indicate that this is a “dark uncertainty image”.
- A bad-pixel status mask should accompany each dark calibration product. This is a FITS image showing those pixels where a dark estimate was not possible, unreliable, low/high relative to neighboring pixels, or highly uncertain (i.e., unstable). “Bad dark” pixels should be flagged with the value 1, otherwise set to 0 if a “good” estimate was possible. The header of this FITS mask image can be the same as above, except that a COMMENT field will need to indicate that this is a “dark calibration mask”.
- Suggested filenames for dark products:
  - *main dark images*: gnddark-w<band>-int-t<temp>-v<version>.fits
  - *uncertainty images*: gnddark-w<band>-unc-t<temp>-v<version>.fits
  - *bad-pixel status masks*: gnddark-w<band>-msk-t<temp>-v<version>.fits
- We would also appreciate if the eventual algorithm used (if different from the above) be forwarded to the WSDC with delivery of the calibration products.

### 3 Flat-field (Responsivity) Correction

- The SDL characterization plan describes a test to calibrate pixel-to-pixel (high frequency) responsivity variations relative to the array mean or median responsivity. This will be accomplished by taking images of a *flat* extended source at a set of temperatures (minimum, nominal and maximum). The plan is to derive flat-field images (and corresponding uncertainties) at each temperature and band, and also perhaps flats that optimally combines the data over all temperatures.
- Here are the pre-processing steps and *suggested* algorithm (some of these still need to be discussed with SDL – they may have already applied some of the pre-calibration steps):
  - It is assumed that all raw data frames have gone through DEB processing (as will be done in-flight) to yield pixel values in effective “slope” units. This is not known at the time of writing. If the test data instead consists of full ramp samples per pixel, then they will first need to be collapsed into effective “slope” units using the same algorithm outlined in the DEB processing document. We advise using the default (nine) SUR multiplication coefficients for now, unless SDL have specified otherwise. If the data is from a band 4 array, remember to down-sample the data (if not already) by *adding* the “slope” signal in every four adjacent pixels and truncating the two least significant bits from the result. This operation is also described in the DEB processing document.
  - For each frame (in “slope” units), the next step involves subtracting off the electronic bias structure (DC offset) from each amplifier channel using the reference (border) pixels. The algorithm is described in Appendix I. The impact of this step on the final noise is still under discussion with the Project Office (contact: Amy Mainzer), and is not yet fully characterized. Apply this correction only to the band 1 and 2 frames. Its impact on band 3 and 4 is still being understood.
  - If droop is present and has been calibrated (see section 6), we suggest that it also be removed. This may only be applicable to the Si:As arrays.
  - We assume that dark images were also taken prior to acquiring the flat-field test data, and that the dark data are already in effective “slope” units (i.e., gone through the DEB algorithm). A dark image (corresponding to same temperature and band) needs to be subtracted from each respective flat-field image. See section 2 for details on creating dark images if not already in the correct format. We assume that detector non-linearity has been calibrated, and software to correct for it exists. The flat-field test data (in “slope” units) needs to be corrected for non-linearity using the appropriate calibration coefficients for the band and temperature in question.
  - The next step involves optimally combining all the “slope” image frames (for a given band and temperature) to create “high SNR” flat-field image products. The responsivity for pixel  $(i, j)$  in an array corresponding to band  $b$ , and for an extended source with temperature  $T$  can be calculated from the  $N$  input frames using:

$$f_{i,j}(b,T) = \frac{S_{i,j}}{S_{norm}} = \frac{\langle S_N(b,T) \rangle_{i,j}}{\langle S_{N,i,j}(b,T) \rangle},$$

where the angled brackets denote either average or median. The numerator is an *average* or *median* for a single pixel  $(i, j)$  over all  $N$  frames in the stack, and the denominator is the same measure computed over *all* pixels and frames in the stack, i.e., it represents the flat-field normalization.

- Either of two methods can be used: simple un-weighted averaging with upper and lower sigma clipping (to reject outliers – see below), or a straight median. A median will give products with slightly higher uncertainty than averaging, however this is a small price to pay given its robustness against outliers. We recommend using a median. There will be enough data to still get a good SNR in the end.
- A corresponding uncertainty image should also be generated for each flat-field image. This contains a 1-sigma error estimate in the responsivity  $f_{i,j}$  in the same units, for every pixel  $(i, j)$ . The uncertainty in the responsivity is given by:

$$\sigma_f = f_{i,j} \sqrt{\left[ \frac{\sigma(S_{i,j})}{S_{i,j}} \right]^2 + \left[ \frac{\sigma(S_{norm})}{S_{norm}} \right]^2},$$

where all quantities were defined above and we have dropped the  $b$  (band) and  $T$  (temperature) labels.

- The method to determine  $\sigma(S_{i,j})$  and  $\sigma(S_{norm})$  in the above equation will depend on the flat-field estimation algorithm used (more specifically, for computing  $S_{i,j}$  and  $S_{norm}$ ). If the median is the method of choice, then a robust measure for its 1-sigma uncertainty can be estimated from either: (i) the sample Median Absolute Deviation (MAD):  $\sigma_m = 1.8577 * \text{median}\{|p_i - \text{median}\{p_i\}|\} / \sqrt{N}$ , where  $N$  is the number of values in a pixel stack, or (ii) the quantile difference:  $\sigma_m = 1.2533 * 0.5 * [q_{0.8413} - q_{0.1586}] / \sqrt{N}$ . The numerical factors account for the fact that the median is noisier than the mean, assuming the underlying population is Gaussian. If adamant on using trimmed averaging, we suggest the following procedure for a pixel stack: (i) compute a robust measure of the dispersion, e.g.,  $\sigma_d = 0.5 * [q_{0.8413} - q_{0.1586}]$ ; (ii) also compute the median  $m$ ; (iii) flag or omit outlying pixels with values  $p < m - n * \sigma_d$  and  $p > m + n * \sigma_d$  where  $n = 4$  or  $5$  (your choice); (iv) compute the mean  $\mu$  and standard deviation ( $SD$ ) of the remaining  $N$  samples in the stack. The mean is the calibration estimate and its uncertainty will be  $\sigma_\mu \sim SD / \sqrt{N}$ . Note: for  $\sigma(S_{norm})$ , the  $N$  is actually the total number of pixels across *all frames*. Thus,  $\sigma(S_{norm})$  will be negligible.
- If there is a desire to combine all the flat-field images across the three test temperatures (for a given band  $b$ ), then this can be accomplished using an inverse-variance weighted average:

$$f_{i,j}(b) = \frac{\frac{f_{i,j}(T_1)}{\sigma_f^2(T_1)} + \frac{f_{i,j}(T_2)}{\sigma_f^2(T_2)} + \frac{f_{i,j}(T_3)}{\sigma_f^2(T_3)}}{\frac{1}{\sigma_f^2(T_1)} + \frac{1}{\sigma_f^2(T_2)} + \frac{1}{\sigma_f^2(T_3)}};$$

$$\sigma_f^2(b) = \frac{1}{\frac{1}{\sigma_f^2(T_1)} + \frac{1}{\sigma_f^2(T_2)} + \frac{1}{\sigma_f^2(T_3)}}.$$

- *Cautionary note:* beware of vignetting towards the edges of an array where the wells may not be sufficiently filled. We will want to ensure that the wells are filled uniformly over an array. If not, this will show up as a variation in the uncertainty estimates over an array, and also possibly in the responsivity estimates too.
- The format for the flat-field images shall be in the Flexible Image Transport System (FITS). A sample FITS header is below. The angle brackets indicate information whose literal content depends on actual execution or generation circumstances.

```

SIMPLE =          T / file does conform to FITS standard
BITPIX =          -32 / number of bits per data pixel
NAXIS  =           2 / number of data axes
NAXIS1 =         <Num> / length of data axis 1
NAXIS2 =         <Num> / length of data axis 2
BAND   =         <Num> / WISE band number (1, 2, 3 or 4)
TEMP   =         <x.x> / Array test temperature in Kelvin
VERSION =        <x.x> / Version of calibration product
COMMENT WISE Flat-field calibration product, created <YYYY-MM-DD>
COMMENT by <Joe Astronomer> at <institute name>
COMMENT created from data set <ID of test data or description>

```

*Notes:*

- BITPIX = -32 refers to single precision floating point.
- For bands 1, 2 and 3, NAXIS1 = NAXIS2 = 1024. For band 4, NAXIS1 = NAXIS2 = 512. This implies the 4-pixel wide reference border in bands 1, 2 and 3, and 2 pixels wide in band 4 should be carried through the flat-field estimation process and retained in the final FITS products. It will be appropriately dealt with in processing at the WSDC.
- The VERSION keyword refers to the version number (e.g., v. 1.0 for initial version) of the calibration product. This is in case it is re-created using different inputs or methods later.
- The *last* COMMENT line stores information on the data set from which the calibration product was created. This can be an ID for the test batch if available, or, the lab location and date where the test data was acquired.
- The corresponding uncertainty image should be stored in a separate FITS file. The header of this FITS image can be the same as above, except that a COMMENT field will need to indicate that this is a “flat-field uncertainty image”.
- A bad-pixel status mask should accompany each flat-field calibration product. This is a FITS image showing those pixels where a responsivity estimate was not possible, unreliable, low/high relative to neighboring pixels, or highly uncertain (i.e., unstable). “Bad responsivity” pixels should be flagged with the value 1, otherwise set to 0 if a “good” estimate was possible. The header of this FITS mask image can be the same as above, except that a COMMENT field will need to indicate that this is a “flat-field calibration mask”.
- Suggested filenames for flat-field products:
  - *main flat-field images:* gndflat-w<band>-int-t<temp>-v<version>.fits
  - *uncertainty images:* gndflat-w<band>-unc-t<temp>-v<version>.fits
  - *bad-pixel status masks:* gndflat-w<band>-msk-t<temp>-v<version>.fits

- We would also appreciate if the eventual algorithm used (if different from the above) be forwarded to the WSDC with delivery of the calibration products.
- The WSDC will apply *low-frequency* correction maps to the high-frequency responsivity maps before using them in production. The low-frequency maps characterize throughput variations when light goes through the entire WISE optical train. This includes (predominately) the convergence and divergence of rays due to optical distortion. There is a plan to derive low-frequency maps in IOC by mapping the same star at different locations and measuring relative changes in its brightness. It would be desirable to obtain low-frequency flats on the ground if time permits. This is not in the SDL characterization plan.

#### 4 Non-linearity Correction

- As outlined in the SDL characterization plan, the non-linearity will be calibrated from Sample-Up-the-Ramp (SUR) data consisting of repeated observations of a uniform scatter source that's moved on the array and with a range of intensity levels up to saturation in the ADC. This test will enable non-linearity coefficients to be derived for every pixel in the active region of each array.
- The test will be repeated at three different temperatures (minimum, nominal and maximum), and we envisage non-linearity coefficients to be derived for each.
- It will be advantageous to have the ramp test data in FITS image format (possibly a FITS cube) with a plane assigned to each of the 9 nominal SUR samples. This will allow usage in existing WSDC software and tools.
- The processing steps that need to be applied to each of the 9 sample image planes are as follows (please check with SDL to ensure these haven't been applied):
  - Subtract the electronic bias structure (DC offset) from each amplifier channel using the reference (border) pixels. The algorithm is described in Appendix I. The impact of this step on the final noise is still under discussion with the Project Office (contact: Amy Mainzer), and is not yet fully characterized. Apply this correction only to the band 1 and 2 frames. Its impact on band 3 and 4 is still being understood.
  - If droop is present and has been calibrated (see section 6), we suggest that it also be removed. This may only be applicable to the Si:As arrays.
  - If SUR darks exist (for each of the 9 sample planes and for the same experimental test setup, e.g., temperature and exposure times), then we suggest that these also be subtracted from the respective sample image planes.
  - The first “zeroth” SUR sample should be subtracted from all other samples in the ramp of a frame. This will force the baseline to zero and prevent fitting of an unnecessary intercept parameter when calibrating the non-linearity.
- For each of the 9 sample images of a frame, uncertainty estimates are needed to assist in the non-linearity fitting. These can be based on a simple Poisson + read noise model given knowledge of the gain. The uncertainties can also be computed *a posteriori* from the variance across repeated measurements if available. The sigma-images (1-sigma value for every pixel and ramp sample) can be stored in the same FITS cube format as the input data.

- We are now ready to fit a non-linearity model to the reduced SUR image data, incorporating uncertainty estimates as described above. We suggest first fitting a *quadratic* model to the ramp data for *every* pixel. If the fit is not acceptable (to within uncertainties), a *cubic* model should be fit. Other functions may provide a better fit, so it is advised to experiment. We can decide later using goodness of fit tests on the “best” model for each band. The quadratic and cubic representations are respectively as follows:

$$y_n(obs) = \alpha n^2 + \beta n,$$

$$y_n(obs) = \alpha n^3 + \beta n^2 + \gamma n,$$

where

$y_n(obs)$  = measured SUR value at sample  $n$  :

$n = 0, 1, 2, 3, 4, 5, 6, 7, 8$  for the 9 SUR samples.

- The WSDC has devised a scheme to linearize the native “slope” data output from the DEB in its pipeline processing. This depends on having the non-linearity calibrated in the above format. In a nutshell, the *observed* DEB “slope” value ( $m_{obs}$ ) can be written in terms of its linearized counterpart ( $m_{lin}$ ) after dark subtraction as follows. For the quadratic and cubic models respectively:

$$m_{obs} = C_1 m_{lin}^2 + m_{lin}; \quad \text{where } C_1 = \frac{\alpha \sum_{n=0}^8 c_n n^2}{\beta^2 \left[ \sum_{n=0}^8 c_n n \right]^2}; \quad c_n = 9 \text{ SUR coefficients (weights);}$$

$$m_{obs} = C_1 m_{lin}^3 + C_2 m_{lin}^2 + m_{lin}; \quad \text{where } C_1 = \frac{\alpha \sum_{n=0}^8 c_n n^3}{\gamma^3 \left[ \sum_{n=0}^8 c_n n \right]^3}; \quad C_2 = \frac{\beta \sum_{n=0}^8 c_n n^2}{\gamma^2 \left[ \sum_{n=0}^8 c_n n \right]^2}.$$

If the derivation is not immediately obvious, please contact F. Masci. These can be inverted to solve for  $m_{lin}$ . Inversion of the quadratic case is straightforward. For the cubic case however, it may be more reliable to fit a new function/polynomial to data pairs ( $m_{obs}$ ,  $m_{lin}$ ) and making  $m_{lin}$  the dependent variable. This removes the ambiguity of deciding between degenerate solutions. The above is purely for your information, and it does not enter in the derivation of the linearity coefficients ( $\alpha$ ,  $\beta$ ) or ( $\alpha$  and  $\beta$ ,  $\gamma$ ).

- The parameters (best fit coefficients) can be estimated using a standard linear least-squares, or more specifically,  $\chi^2$  minimization if prior uncertainties are available. The estimation for polynomials is linear and analytic, and goodness of fit measures can be derived too. This procedure has been previously coded in a generic Fortran program that was used on *Spitzer*: *lincal*. This program conveniently reads multiple FITS cubes (corresponding to the *same* illumination level), finds and flags outliers in a ramp, generates the full error-covariance matrix for all parameter estimates, and stores the results in a FITS cube. We’ll leave the choice to you.

- The *non-linear* coefficients  $\alpha$  for the quadratic model, or,  $\alpha$  and  $\gamma$  for the cubic model should generally come out to be negative since these are what make the ramps deviate from linearity. If they are significantly  $> 0$ , then it indicates that either something has gone wrong in the fitting, the ramp for that pixel does not behave as expected (e.g., it's a bad pixel), or, a particular ramp sample was affected by a (missed) outlier. If any coefficient estimates are consistent with zero (within their uncertainty), then it means those ramps and pixels are linear.
- If the non-linear coefficients turn out to be constant over an array, i.e., are overall consistent within each pixel's uncertainty (ignoring bad fits, i.e., due to bad pixels), we can assume global coefficients for the entire array. These should be derived using some optimal combination of all the pixel coefficients and uncertainties. This will make life easy. Highly non-linear pixels can later be flagged in a bad-pixel mask (e.g., as defined in section 7).
- We also advise checking that the non-linearity factors  $C_1$  or ' $C_1$  and  $C_2$ ' (for cubic), as applied to the DEB slope data (see equations above) are independent of the illumination level of a ramp. This check assumes several ramps at different illumination are available. This translates to the observed DEB slope  $m_{obs}$  (as derived on-board) *not* depending on the  $C_x$ . This is implicit in the derivation leading to the above equations. If a dependency exists, we need to revise the non-linearity algorithm.
- Cautionary notes and advisories before fitting:
  - Beware of bad pixels, i.e., as flagged *a priori* in bad-pixel masks if available (section 7). If inadvertently ignored, you'll probably get bad fits and non-linearity estimates.
  - Beware of outliers in a ramp. Omission of outliers prior to combining the data for fitting is strongly recommended.
  - Beware of any depression effects early on in a ramp - e.g., the first sample. These samples *may* need to be excluded and the ramps re-baselined to start at zero on the second sample before fitting. At the time of writing, this may pertain to only bands 1 and 2, where the first (zeroth exposure time sample) is ignored in the DEB slope estimation.
  - Also beware of any "hook-like" or weirdly non-linear, non-monotonic behavior anywhere in a ramp. If such features are systematic, it may require a revision of the non-linearity algorithms, e.g., instead of using analytic functions, we use look-up tables or interpolate.
  - Beware of vignetting towards the edges of an array where the wells may not be sufficiently filled. In the end, we will want to sample the *full* dynamic range for every pixel on an array.
- WSDC receivables and formats:
  - If  $C_1$  or ' $C_1$  and  $C_2$ ' (for cubic) are ~the same from pixel-to-pixel (i.e., within each others' uncertainties), then a simple table in ASCII format would suffice. This table should indicate the band number;  $C_x$  estimates; their 1-sigma uncertainties, and the temperature of the test if applicable. Note: the uncertainties in the  $C_x$  also depend on the covariances between the fitted coefficients. We assume these will be accounted for in the uncertainty estimation process.
  - If *significantly different* non-linearity coefficients are found across pixels, then we request that the information be stored in single plane FITS files for each band and temperature if applicable. For the quadratic case for example, this means 8 FITS files across bands for a single temperature. For the cubic, it's 16. A sample FITS header is below. The angle brackets

indicate information whose literal content depends on actual execution or generation circumstances.

```

SIMPLE = T / file does conform to FITS standard
BITPIX = -32 / number of bits per data pixel
NAXIS = 2 / number of data axes
NAXIS1 = <Num> / length of data axis 1
NAXIS2 = <Num> / length of data axis 2
BAND = <Num> / WISE band number (1, 2, 3 or 4)
TEMP = <x.x> / Array test temperature in Kelvin
MODEL = '<string>' / Non-linearity model: quad or cubic
VERSION = <x.x> / Version of calibration product
COMMENT WISE Non-Linearity calibration product, created <YYYY-MM-DD>
COMMENT by <Joe Astronomer> at <institute name>
COMMENT created from data set <ID of test data or description>
COMMENT product: <C1 or C2 or sigma_C1 or sigma_C2>

```

- BITPIX = -32 refers to single precision floating point.
  - For bands 1, 2 and 3, NAXIS1 = NAXIS2 = 1024. For band 4, NAXIS1 = NAXIS2 = 512. This implies the 4-pixel wide reference border in bands 1, 2 and 3, and 2 pixels wide in band 4 should be carried through the non-linearity estimation process and retained in the final FITS products. It will be appropriately dealt with in WSDC processing.
  - The VERSION keyword refers to the version number (e.g., v. 1.0 for initial version) of the calibration product. This is in case it is re-created using different inputs or methods later.
  - The *third* COMMENT line from the top stores information on the data set from which the calibration product was created. This can be an ID for the test batch if available, or, the lab location and date where the test data was acquired.
  - The last COMMENT line indicates the flavor of calibration product.
- A bad-pixel status mask should accompany each non-linearity calibration product corresponding to band and test temperature (if applicable). This is a FITS image showing those pixels where a non-linearity estimate was not possible, unreliable, or highly uncertain. “Bad non-linearity” pixels should be flagged with the value 1, otherwise set to 0 if a “good” estimate was possible. The header of this FITS mask may be the same as in the above example, with a COMMENT field indicating that this is a “non-linearity calibration mask”.
  - Suggested filenames for the non-linearity calibration products (if derived on a per-pixel basis and hence stored in FITS format):
    - *main cal products*: gndlincal-w<band>-est<n>-t<temp>-v<version>.fits
    - *uncertainty images*: gndlincal-w<band>-unc<n>-t<temp>-v<version>.fits
    - *bad-pixel status masks*: gndlincal-w<band>-msk-t<temp>-v<version>.fits
 where <n> is a number (1 or 2) for cases where there is more than one calibration factor (e.g.,  $C_1$  and  $C_2$  for the cubic model).
  - We would also appreciate if the eventual algorithm used (if different from the above) be forwarded to the WSDC with delivery of the calibration products.



## 5 Gain and Read-Noise Maps

- First, we define the “gain” in the context of an *electronic gain factor* indicating how many electrons correspond to an Analog Digital Unit (ADU) or Data Number (DN) for any sample in a ramp. This number will allow us to estimate *prior* uncertainties using a noise model. The question is: will this gain factor vary appreciably from pixel-to-pixel? Initial thoughts are that it should more-or-less follow the variation in pixel-to-pixel responsivity.
- A test to measure the gain factor *per pixel* was not explicitly mentioned in the SDL characterization plan. However, this can be derived from data intended for other calibrations (e.g., flats and/or non-linearity). The same applies to measuring the read-noise on a *per pixel* basis. There are plans to estimate the read-noise for each array (and pixel) using dark data, e.g., from the RMS in stacks of darks acquired from repeated measurements. One must ensure that the dark signal was approximately constant over the observation span (and if not, de-trended) to avoid the RMS (hence read-noise) estimates being affected by detector instabilities. Nonetheless, both the gain and read-noise per pixel can be derived simultaneously from ancillary data. Below we outline two methods.
- **The first method** involves using FEB (SUR) data at different illumination levels with measurements repeated at each of the illuminations. The FEB data may be from the non-linearity test and will allow an estimation of the gain and read-noise at single ramp samples, as needed in the WSDC pipeline. The method entails performing a linear least-squares fit of the model variance equation (Poisson + read-noise) to ensembles of frames at different illumination levels (below saturation). For pixel  $i, j$  in a FEB “sample” frame, we fit:

$$\sigma_{DN}^2 = \frac{S_{DN}}{g(i,j)} + K(i,j),$$

where :

$\sigma_{DN}^2$  = variance in pixel  $i, j$  over ensemble of images at a given illumination;

$S_{DN}$  = mean signal in pixel  $i, j$  in ADU over ensemble;

$g(i,j)$  = gain in electrons/ADU;

$$K(i,j) = \frac{\sigma_{RN}^2(i,j)}{g(i,j)^2};$$

$\sigma_{RN}^2(i,j)$  = readnoise variance where  $\sigma_{RN}$  is in electrons/pixel.

The above equation is fit to ensembles of frames at single FEB samples where each ensemble corresponds to a different illumination level. For each ensemble, we estimate the mean (or median) signal  $S_{DN}(i,j)$  and variance  $\sigma_{DN}^2(i,j)$ . The gain and read-noise can then be derived from the slope ( $1/g$ ) and intercept ( $K$ ) fit to each pixel  $i, j$ . One can also make use of the prior read-noise estimated from the dark DEB data (properly converted to apply to single ramp samples) to assist in estimating the gain.

**The second method** involves fitting the full DEB noise model (Eq. 16 in the WISE Pixel Error Model document referenced in §1.2) to DEB data taken at different illuminations ( $m$ ). If repeated

measurements at each illumination are not available, then a per-pixel estimation of the signal variance ( $\sigma_m^2$ ) and hence gain and read-noise will not be possible. Instead, a region on each frame with a given illumination will need to be carefully chosen (i.e., containing few bad pixels) for computing the variance. One can also make use of the prior read-noise estimated from the dark DEB data (properly converted to apply to single ramp samples as represented in this equation) to assist in estimating the gain.

- If gain and read-noise maps can be derived, we request that their format be in the Flexible Image Transport System (FITS). A sample FITS header is below. The angle brackets indicate information whose literal content depends on actual execution or generation circumstances.

```

SIMPLE =                               T / file does conform to FITS standard
BITPIX =                               -32 / number of bits per data pixel
NAXIS  =                               2 / number of data axes
NAXIS1 =                               <Num> / length of data axis 1
NAXIS2 =                               <Num> / length of data axis 2
BAND   =                               <Num> / WISE band number (1, 2, 3 or 4)
VERSION =                              <x.x> / Version of calibration product
BUNIT  =                               `units` / Units of image data
COMMENT WISE gain (or read-noise) map, created <YYYY-MM-DD>
COMMENT by <Joe Astronomer> at <institute name>
COMMENT created from data set <ID of test data or description>

```

*Notes:*

- BITPIX = -32 refers to single precision floating point.
- For bands 1, 2 and 3, NAXIS1 = NAXIS2 = 1024. For band 4, NAXIS1 = NAXIS2 = 512. This implies the 4-pixel wide reference border in bands 1, 2 and 3, and 2 pixels wide in band 4 should be carried through the gain/read-noise estimation process and retained in the final FITS products. It will be appropriately dealt with in processing at the WSDC.
- The VERSION keyword refers to the version number (e.g., v. 1.0 for initial version) of the calibration product. This is in case it is re-created using different inputs or methods later.
- BUNIT specifies the image data units. For gain maps the units are electrons/ADU; for read-noise maps the units are *electrons*.
- The *last* COMMENT line stores information on the data set from which the calibration product was created. This can be an ID for the test batch if available, or, the lab location and date where the test data was acquired.
- A bad-pixel status mask should accompany the gain and read-noise maps for each band (if possible). This is a FITS image showing those pixels where a gain or read-noise estimate was not possible, unreliable, abnormally low/high relative to neighboring pixels, or highly uncertain (i.e., unstable). “Bad gain or read-noise” pixels should be flagged with the value 1, otherwise set to 0 if “good” estimates were possible. The header of this FITS mask image can be the same as above, except that a COMMENT field will need to indicate that this is either a gain or read-noise “calibration mask”.
- Suggested filenames for gain and read-noise maps:
  - *gain maps*: gndgain-w<band>-map-v<version>.fits
  - *read-noise maps*: gndrnoise-w<band>-map-v<version>.fits

- *gain map masks*: gndgain-w<band>-msk-v<version>.fits
- *read-noise map masks*: gndrnoise-w<band>-msk-v<version>.fits

## 6 Droop Correction

- This section assumes the “droop effect” is the same as that seen in the *Spitzer* Si:As arrays. Here, droop was an erroneous signal that was added to the output from a pixel and whose magnitude was proportional to the total signal (electrons read) from the array. In other words, a global coupling existed between the readout channels and/or amplifiers. This should not be confused with Inter-Pixel Capacitance (IPC), which operates on local pixel-to-pixel scales. The SDL characterization plan outlines a test to assess and measure droop. Before proceeding with the below, it is recommended that the following document on droop mitigation and its impact be read: [http://web.ipac.caltech.edu/staff/fmasci/home/wise/Droop\\_question.pdf](http://web.ipac.caltech.edu/staff/fmasci/home/wise/Droop_question.pdf)
- It is assumed that all raw data frames from the droop experiment have gone through DEB processing (as will be done in-flight) to yield pixel values in effective “slope” units. This uses the algorithm outlined in the DEB processing document referenced in section 1. Also, it is assumed that band 4 data frames have already been down-sampled. This operation is also described in the DEB processing document.
- No other pre-processing steps are needed prior to assessing and measuring droop.
- It is expected that the presence of droop will be assessed (and quantified if present) for each array separately.
- Here we describe the details on how to use the SDL test data to assess and calibrate droop. The test first involves illuminating a WISE array with a uniform stim source and then measuring its signal over all pixels  $i$ :  $S_i^{stim}$  (where  $i = 1 \dots N_i$ ;  $N_i = 1016^2$  for bands 1, 2, 3, and  $508^2$  for band 4 if already down-sampled). A point source is then placed somewhere on the array spanning an effective pixel region  $j = 1 \dots N_j$  and its intensity is varied. The *point source* signal in a pixel within this region is given by:  $P_j = S_j^{tot} - S_j^{stim}$ . The presence of droop can be assessed by seeing if there is a change in pixel signal at some location  $i$  away from the point source location ( $\Delta S_i$ ) as the average point source signal over  $j = 1 \dots N_j$  is varied. In essence, the *before* point source turn-on (stim only image) can be subtracted from the *after* image. If there is a statistically significant excess signal at locations away from the point source, then droop is present. If present, the next step is to calibrate the droop signal.
- The droop signal can be quantified by regressing these quantities against each other to derive a linear droop coefficient (coupling constant) for pixel  $i$  with point source located at centroid  $j_c$ :  $C_d(i, j_c)$ :

$$\Delta S_i = C_d(i, j_c) \langle P_j \rangle$$

where :

$$\langle P_j \rangle = \frac{1}{N_j} \sum_{j=1}^{N_j} P_j$$

$$\Delta S_i = S_i^{after} - S_i^{before},$$

$$P_j = S_j^{tot(after)} - S_j^{stim(before)}.$$

- On the *Spitzer* Si:As arrays, the droop signal was seen to depend linearly on total intensity over an array, and the droop coefficient was independent of location and total intensity. Thus, it was treated as a constant:  $C_d(i, j_c) = C_d$ . We expect the same will apply to WISE, and there will be enough test data to justify (or invalidate) this. We suggest deriving a droop coefficient for many pixel locations  $i$ , and also many point source positions  $j_c$  (if the data is available). If the estimates  $C_d(i, j_c)$  do not significantly differ with  $i$  and  $j_c$  (i.e., are within each others' uncertainties – see below), they can be averaged to derive a single droop coefficient  $C_d$ . Alternatively, the signal data from the different  $i$  and  $j_c$  locations can be combined into the same fit.
- The derivation of  $C_d(i, j_c)$  entails fitting the above equation to measures of  $\Delta S_i$  versus  $\langle P_j \rangle$  using standard least squares methods. Note that both  $\Delta S_i$  and  $\langle P_j \rangle$  are random variables and subject to measurement uncertainty. The uncertainty in the “slope”  $C_d(i, j_c)$  can be estimated from the variance in residuals about the best line fit. If errors in  $\langle P_j \rangle$  are small (and hence assuming these are your fixed “x” values), then the uncertainty in  $C_d(i, j_c)$  follows from standard  $\chi^2$  or linear-regression methods (i.e., canned routines in IDL, Numerical Recipes). If errors in  $\langle P_j \rangle$  are appreciable so that you have errors in both  $x$  and  $y$ , then the uncertainty estimation is more difficult. The author is unaware of canned routines for this case. One can instead use a Monte Carlo method for estimating uncertainties in  $C_d(i, j_c)$ , where the errors for the  $x$  and  $y$  measurements are first estimated from the variance in residuals about a best line fit.
- We advise that data containing bad pixels (i.e., masked *a priori* – see section 7) be omitted from the fits.
- In summary, we request that a table in ASCII format containing the 4 droop coefficients (one for each array) with respective 1-sigma uncertainties be delivered to the WSDC. This assumes a constant droop coefficient was found for each array. We would also appreciate if the eventual algorithm used (if different from the above) be forwarded to the WSDC with delivery of the calibration products.
- SDL have also proposed a reverse of the above experiment where a constant point source is placed on an array, and then the uniform stim level is varied instead. This can also be used to ascertain the presence of droop by differencing the *before* and *after* stim-change images, and determining whether there is a residual (droop) signal at the point source location. The above formalism to derive the droop coefficient does not assume data from this second test, although it can be easily extended to include it. We'll leave the decision to the analyst.

- For your information, droop will be corrected in the instrumental calibration pipeline using the following equation. The true (after droop-corrected) signal in pixel  $i$  is given by:

$$S_i^{true} \approx S_i^{meas} - \frac{C_d}{N} \sum_{j=1}^N S_j^{meas}.$$

If any pixels were flagged as saturated after ADC, their total underlying (de-saturated) signal must first be estimated before adding their contribution to the sum term.

## 7 “Bad” Pixel (Static) Status Masks

The “bad” pixel status mask stores *a priori* information for those pixels which do not perform within requirements or as expected. Each band shall have a “static” bad-pixel mask derived from ground characterization, and updated in flight if needed. Furthermore, these may be updated at the WSDC to include information from the individual calibration masks described above (e.g., from the explicit derivation of darks, flats, non-linearity, gain and read-noise maps). This mask will be combined with a larger (32-bit) dynamic mask derived from flight data for use in the instrumental calibration pipeline (see <http://web.ipac.caltech.edu/staff/fmasci/home/wise/InstruCal01.txt>). Flagging conditions, criteria and thresholds (for both the ‘active’ and ‘reference’ pixels) are TBD. Below is a first attempt to define some of the conditions.

The static mask is a single plane of  $1024 \times 1024$  pixels for bands 1, 2 and 3; and  $512 \times 512$  pixels for band 4, i.e., pixels corresponding to the reference pixel border should be included. The pixels are represented as 8-bit unsigned integers (BITPIX = 8). The status of certain conditions will be assigned to individual bits. Bits are numbered from zero (the LSB) to 7. Each status bit describes a specific condition of the pixel; if the bit has the value 1, the condition is in effect; zero implies that the condition is not in effect. More than one condition may apply to the same pixel.

A sample FITS header is as follows, where the angle brackets indicate information whose literal content depends on actual execution or generation circumstances.

```
SIMPLE = T / file does conform to FITS standard
BITPIX = 8 / number of bits per data pixel
NAXIS = 2 / number of data axes
NAXIS1 = <Num> / length of data axis 1
NAXIS2 = <Num> / length of data axis 2
BAND = <Num> / WISE band number (1, 2, 3 or 4)
VERSION = <x.x> / Version of calibration product
COMMENT WISE bad-pixel mask, created <YYYY-MM-DD>
COMMENT by <Joe Astronomer> at <institute name>
COMMENT created from data set <ID of test data or description>
END
```

*Notes:*

- BITPIX = 8 refers to 1-byte integer format where the range of pixel values is 0 to 255.

- For bands 1, 2 and 3, NAXIS1 = NAXIS2 = 1024. For band 4, NAXIS1 = NAXIS2 = 512. This implies the 4-pixel wide reference border in bands 1, 2 and 3, and 2 pixels wide in band 4 should be retained.
- The VERSION keyword refers to the version number, (e.g., v. 1.0 for initial version) of the calibration product, in case it is re-created using different input data, or flagging criteria later.
- The *last* COMMENT line stores information on the data set from which the calibration product was created. This can be an ID for the test batch if available, or, the lab location and date where the test data was acquired.

Suggested filenames for the ground masks are: `gndmask-w<band>-msk-v<version>.fits`

### Status Bit Definitions (specific criteria TBD):

Bit #	Condition
0	excessive dark current
1	excessive read noise
2	dead pixel (unresponsive)
3	low responsivity (not quite dead)
4	high responsivity (hot)
5	neighbor to hot pixel affected by IPC
6	highly non-linear response
7	undefined

## 8 FOV Distortion Calibration

- First, for a background on distortion and its representation in the science data, we advise you take a look at: <http://web.ipac.caltech.edu/staff/fmasci/home/wise/codeVdist.html>
- We would like to receive distortion vectors ( $\Delta x$ ,  $\Delta y$ ) for each point in a grid spanning each focal plane. We will use these to do our own polynomial fits. This will allow us to choose the order that works best for each array, as well as encode the polynomial coefficients in the correct format needed by the WSDS pipelines.
- For data coming from an optical model such as Code-V, it would be desirable to have a fine grid with about 100 native pixels ( $10 \times 10$ ) in each grid point. That would give us a grid over the FOV consisting of  $\sim 102 \times 102$  vectors.
- For data coming from optical bench measurements, we'll settle for the finest grid possible under the experimental setup. In addition to distortion vectors, it would be desirable to have estimates of their  $1-\sigma$  uncertainties too.
- We envisage a set of distortion vectors to be measured/modeled for a number of different scan-mirror positions (e.g., middle and at both ends). Effective/overall distortion vectors will then need to be derived that combines the data at all mirror positions.

- Since we have concerns about whether optical bench measurements can provide the needed resolution, we will need the Code-V model data at minimum. Of course, both would be nice.
- The distortion vectors can be provided in a table (one for each band) in ASCII format that lists:  $x$ ,  $y$ ,  $\Delta x$ ,  $\Delta y$ ,  $\sigma(\Delta x)$ ,  $\sigma(\Delta y)$  in native pixel units. The uncertainties  $\sigma$  only apply to lab measurements (see above).

## 9 Point Response Functions

- The definition of Point Response Function (PRF) in this context is that resulting when light from a point source goes through the entire WISE optical train, is convolved with the pixel response, and then sampled by the pixels of a FPA to yield the measurements. In other words, it's the profile of a point source as measured off an image. This is sometimes referred to as the Point Spread Function (PSF), however, we reserve PSF to mean the profile resulting from the optical system alone, i.e., with no sampling by a detector.
- As outlined in the SDL characterization plan, PRFs will be characterized with a collimated source in a  $5 \times 5$  grid of array locations at 5 positions of the scan-mirror. We envisage that for each mirror and array position, a number of repeated images will have been taken to enable a high sign-to-noise ratio PRF to be determined. The goal from the lab measurements is to broadly determine the degree of non-isoplanicity over each of the four FPAs, not necessarily to derive finely sampled PRFs for use in production. PRFs to the desired accuracy for profile fitting photometry will be measured in IOC.
- It is assumed that all raw data frames for PRF determination will have gone through DEB processing (as will be done in-flight) to yield pixel values in effective "slope" units. This uses the algorithm outlined in the DEB processing document referenced in section 1. Also, it is assumed that band 4 data frames have already been down-sampled. This operation is also described in the DEB processing document.
- It is envisaged that an accompanying set of darks, flats and non-linearity corrections will be available to perform a basic calibration of the PRF images. The order of the calibration steps is as follows: (i) Subtraction of the electronic bias structure (DC offset) from each amplifier channel using the reference (border) pixels. The algorithm is described in Appendix I; (ii) If droop is present and has been calibrated (see section 6), we suggest that it also be removed (may only be applicable to the Si:As arrays); (iii) Dark subtracted using dark images for each respective band; (iv) Linearity corrected; (v) Responsivity (flat) corrected.
- When the calibration steps have been performed, each set of frames corresponding to the same array-grid location, i.e., the 5 the scan-mirror positions and any repeats can be combined. We recommend using a median rather than an average. For the planned  $5 \times 5$  grid of array locations, this will result in 25 PRF images per band.
- The format for the PRF images shall be in the Flexible Image Transport System (FITS). A sample FITS header is below. The angle brackets indicate information whose literal content depends on actual execution or generation circumstances.

```

SIMPLE = T / file does conform to FITS standard
BITPIX = -32 / number of bits per data pixel
NAXIS = 2 / number of data axes
NAXIS1 = <Num> / length of data axis 1
NAXIS2 = <Num> / length of data axis 2
CRPIX1 = <0.5*(Num + 1)> / reference pixel for axis 1
CRPIX2 = <0.5*(Num + 1)> / reference pixel for axis 2
CTYPE1 = 'RA---SIN' / projection type for axis 1
CTYPE2 = 'DEC--SIN' / projection type for axis 2
CDELT1 = -0.000190972222 / axis 1 scale [deg/pix]
CDELT2 = 0.000190972222 / axis 2 scale [deg/pix]
FPALOCX = <X> / center x coord of grid square
FPALOCY = <Y> / center y coord of grid square
BAND = <BandNum> / WISE band number (1, 2, 3 or 4)
VERSION = <x.x> / Version of calibration product
COMMENT WISE PRF calibration product, created <YYYY-MM-DD>
COMMENT by <Joe Astronomer> at <institute name>
COMMENT created from data set <ID of test data or description>

```

*Notes:*

- BITPIX = -32 refers to single precision floating point.
- The NAXIS1 (= NAXIS2) keyword values specify the dimensions of the PRF images and these are determined by the maximum extent of the PRF to retain. We suggest truncating a PRF such that the *largest* value in the wings is  $\sim 0.01\%$  of its *peak* value. Also, we request the NAXIS1, NAXIS2 values be odd numbers. This will ensure the center pixel coordinate [CRPIX1, CRPIX2] will be an integral pixel instead of fractional.
- The FPALOCX and FPALOCY keywords specify the location of the PRF in the native  $X, Y$  coordinate system of a frame *without the reference pixels*. Their values refer to the *center coordinates* of a square in the  $N_x \times N_y$  grid of array locations. For example, a  $5 \times 5$  grid will have 25 squares (see Figure 2 in Appendix II). A grid square labeled  $(i, j)$ , where  $1 \leq i \leq N_x$  and  $1 \leq j \leq N_y$ , will have center coordinates:

$$\text{FPALOCX} = \left( \frac{\text{NAXIS1}_f}{N_x} \right) \left( i - \frac{1}{2} \right);$$

$$\text{FPALOCY} = \left( \frac{\text{NAXIS2}_f}{N_y} \right) \left( j - \frac{1}{2} \right),$$

where typically  $(\text{NAXIS1}_f, \text{NAXIS2}_f) = (1016, 1016)$  for WISE bands 1, 2 and 3, and  $(\text{NAXIS1}_f, \text{NAXIS2}_f) = (508, 508)$  for band 4, i.e., the coordinate system spanned by the *active* pixels only. Therefore a band 1 PRF for a grid square located at  $(i, j) = (03, 04)$  will have in its header:  $\text{FPALOCX} = (1016/5) * (3 - 0.5) = 508.0$ , and  $\text{FPALOCY} = (1016/5) * (4 - 0.5) = 711.2$ .

- The VERSION keyword refers to the version number (e.g., v. 1.0 for initial version) of the calibration product. This is in case it is re-created using different inputs or methods later.



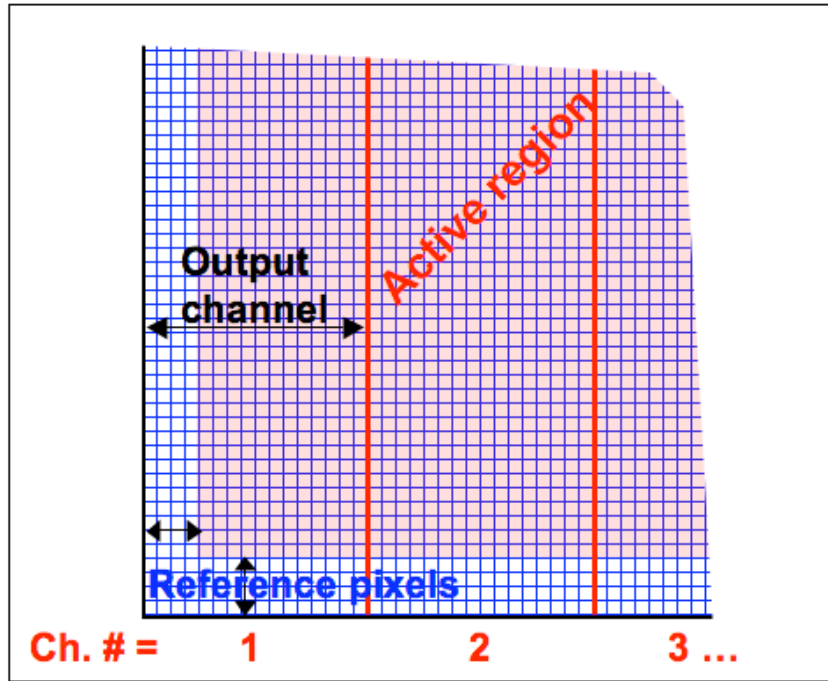
- The *last* COMMENT line stores information on the data set from which the calibration product was created. This can be an ID for the test batch if available, or, the lab location and date where the test data was acquired.
- Suggested filenames for the ground-derived PRF image products are:  
`gndprf-w<band>-prf-<Nx>x<Ny>-<i>x<j>.fits`  
 The  $\langle N_x \rangle$  and  $\langle N_y \rangle$  fields refer to the maximum number of partitions along the X and Y dimensions of a frame respectively at which PRFs were derived, and  $\langle i \rangle$ ,  $\langle j \rangle$  refers to the specific partition in the grid at which the PRF contained in the FITS file corresponds. The convention for the  $\langle i \rangle$ ,  $\langle j \rangle$  locations is illustrated in Figure 2 (Appendix II). The numbering starts at bottom left, and the “fast” dimension is along X.
- We request that each PRF be volume normalized to unity, i.e., the sum of all the pixel values in a PRF image should sum to unity.
- The pixels of each detector are expected to sample the underlying optical PSF at marginally better than the *Nyquist rate* ( $> \sim 2$  native pixels per FWHM of the central beam). The WSDC may therefore resample and interpolate the PRF images to a finer pixel scale (e.g., using *Sinc* interpolation).
- There is also a plan to model PRFs and PSFs using Code-V at *SSG Precision Optronics, Inc.* Here we envisage that the model PSFs can be sampled to arbitrarily small scales. It would be desirable to sample these PSFs at frequencies  $\sim 4 \times$  the characteristic *Nyquist rate*, i.e., at  $\sim 8|v_{\max}|$ , where  $v_{\max}$  is the highest frequency corresponding to the *most significant* structure in the PSF (typically not too far from the central core). Note that the PSFs in bands 1, 2 and 3 are not diffraction limited, but the PSF in band 4 is expected to be. This means the *Nyquist sampling interval*, or maximum allowed pixel size to assume for the band 4 PRFs is  $\sim \lambda/2D$  radians ( $\approx 5.9$  arcsec), where  $D$  is the telescope diameter.
- We request that the model PRFs from Code-V be packaged in the same format as above. The FITS keyword values should be updated accordingly, and all PRFs volume normalized to unity.

## 10 APPENDIX I: Bias/Offset Subtraction using Reference Pixels

Here are the steps. These will need to be optimized (e.g., the moving average window size) when more characterization data becomes available. As a reminder, the impact of this step on the final noise is still under discussion with the Project Office (contact: Amy Mainzer), and is not yet fully characterized. This correction may only apply to bands 1 and 2. Its impact and usefulness on band 3 and 4 is still being understood. Below we describe the procedure for the HgCdTe arrays *only* (bands 1 and 2), as currently implemented in the instrumental calibration pipeline.

1. Before proceeding, it is worth plotting a histogram of the reference pixel values to ensure it looks approximately normal. There are 16,320 reference pixels in the HgCdTe arrays. If there is bi-modal or complicated structure, include this in your final analysis/assessment report and send together with the final calibration products when delivering to the WSDC. Continue on with the next step.

2. For a given output channel (64 native pixels wide in bands 1 and 2 – see Figure 1), average both top and bottom  $2 \times 4 \times 64$  reference pixels. Do this for each output channel to obtain 64 values.
3. Subtract these average values from pixels in the active region in each respective output channel.
4. Compute a row-by-row moving average (in the up/down direction) using both left and right reference pixels. A suggested window (kernel) size for this moving average is 7 rows. In each row-centered window, there will be  $2 \times 7 \times 4 = 56$  pixels to average over.
5. For each pixel row in the range 5 – 1020, i.e., which overlaps with the central active region, subtract the *reference* pixel row moving average value from each *active* pixel in the same row.



**Figure 1:** Schematic of reference and active pixel regions, and amplifier channels for bands 1 and 2.

## 11 APPENDIX II: PRF file naming and location convention

Figure 2 shows an example of a  $5 \times 5$  grid for deriving FPA-position dependent PRFs. Depending on its degree of non-isoplanicity, a PRF will be derived for each of the  $N_x \times N_y$  grid squares or partitions. See Section 9 for details. In general, a PRF calibration product shall have the filename:

```
<calbasename>-w<band>-prf-<Nx>x<Ny>-<i>x<j>.fits
```

Where ground calibrations have  $\langle \text{calbasename} \rangle = \text{gndcal}$ , simulated PRFs have  $\langle \text{calbasename} \rangle = \text{simcal}$ , and on-orbit derived PRFs *may* have  $\langle \text{calbasename} \rangle = \text{flightcal}$ . The  $\langle i \rangle$ ,  $\langle j \rangle$  indices refer to the specific partition in the grid at which the PRF contained in the FITS file corresponds. For example, a ground derived PRF for band-1 at grid square  $(i, j) = (01, 04)$  in Figure 2 will be named: `gndcal-w1-prf-05x05-01x04.fits`.

01,05	02,05	03,05	04,05	05,05
01,04	02,04	03,04	04,04	05,04
01,03	02,03	03,03	04,03	05,03
01,02	02,02	03,02	04,02	05,02
01,01	02,01	03,01	04,01	05,01

**Figure 2:** Example of a  $5 \times 5$  partition of the native frame for deriving FPA-position dependent PRFs. The indexing scheme (as used in filenames) is also shown. See Section 9 for details.