

Instrumental Calibration

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Outline



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 - droop/electronic artifact correction
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Requirements (Level 4)

From the WSDC Functional Requirements Document (Version 2.0; 25 November 2007):

- **L4WSDC-042:** The WSDS Pipeline processing shall remove the instrumental signature from Level 0 image frames.
- **L4WSDC-037:** The WSDC Pipelines subsystem shall convert raw WISE science and engineering data into calibrated images and extracted source lists from which the preliminary and final WISE data products will be derived.
- **L4WSDC-039:** Within 3 days from receipt of a given data set at the WSDC all data shall be processed through the WSDS Scan/Frame pipeline which performs basic image calibration and source extraction from on images from individual orbits. The results of this processing step shall be Level 1 source extractions and image data, which are loaded into the WISE Level 1 extracted Source Working Database (L1WDB) and Image Archive allowing access by the WISE Science Team for external quality assessment.
- **L4WSDC-024:** The WSDC shall generate and maintain an archive of the calibrated, single epoch WISE images for the duration of the project for use by the Project Team. The purposes of this archive are quality assurance, transient analysis and moving object identification. Self-derived Demonstration Define duration of project.
- **L4WSDC-057:** The WSDC shall provide an online repository for operations products for the life of the project.



Requirements continued..



- **L4WSDC-060:** The WSDC archive shall provide a web-based interface to enable selection, display and retrieval of any or all single-epoch images and combined Atlas Images based on position or time of observation for the purpose of quality assurance, validation and analysis. The goal shall be to also allow image selection on any image metadata parameter.
- **L4WSDC-033:** The WSDC shall ingest WISE engineering telemetry that is sent by the MOS. This shall include but may not be limited to spacecraft ephemeris data, spacecraft pointing data, vehicle time-to-UTC conversion data, stored state-of health data, orbit events files and sequence events files. These data shall be combined with the appropriate raw science image data to form WISE Level 0 science images.
- **L4WSDC-012:** Flux measurements in the WISE Source Catalog shall have a SNR of five or more for point sources with fluxes of 0.12, 0.16, 0.65 and 2.6 mJy at 3.3, 4.7, 12 and 23 micrometers, respectively, assuming 8 independent exposures and where the noise flux errors due to zodiacal foreground emission, instrumental effects, source photon statistics, and neighboring sources (*traceable to Level-1*).
- **L4WSDC-013:** The root mean square error in relative photometric accuracy in the WISE Source Catalog shall be better than 7% in each band for unsaturated point sources with SNR>100, where the noise flux errors due to zodiacal foreground emission, instrumental effects, source photon statistics, and neighboring sources. This requirement shall not apply to sources that superimposed on an identified artifact (*traceable to Level-1*).





Frame Processing Flow



Instrument Calibration

INPUTS:

- raw "level-0" FITS frame
- default/ground calibrations

Mask initialization and checks

Flag known "bad" pixels in a processing mask

CAL

Initialize uncertainty image using error model

Bias/offset correction using Reference pixels

Rad-hit & "sharp edge" artifact detection: to supplement temporal method later (TBD)

Droop/electronic corrections

Dark subtraction

CAL

Non-linearity correction

CAL

Input for Flatcal PL

Responsivity (flat) correction

CAL

Input for Skycorr PL

Sky-offset correction

CAL

Frame QA metrics/statistics

OUTPUTS:

- instrumentally calibrated FITS frame
- bit-mask storing processing status
- uncertainty image frame
- QA diagnostics



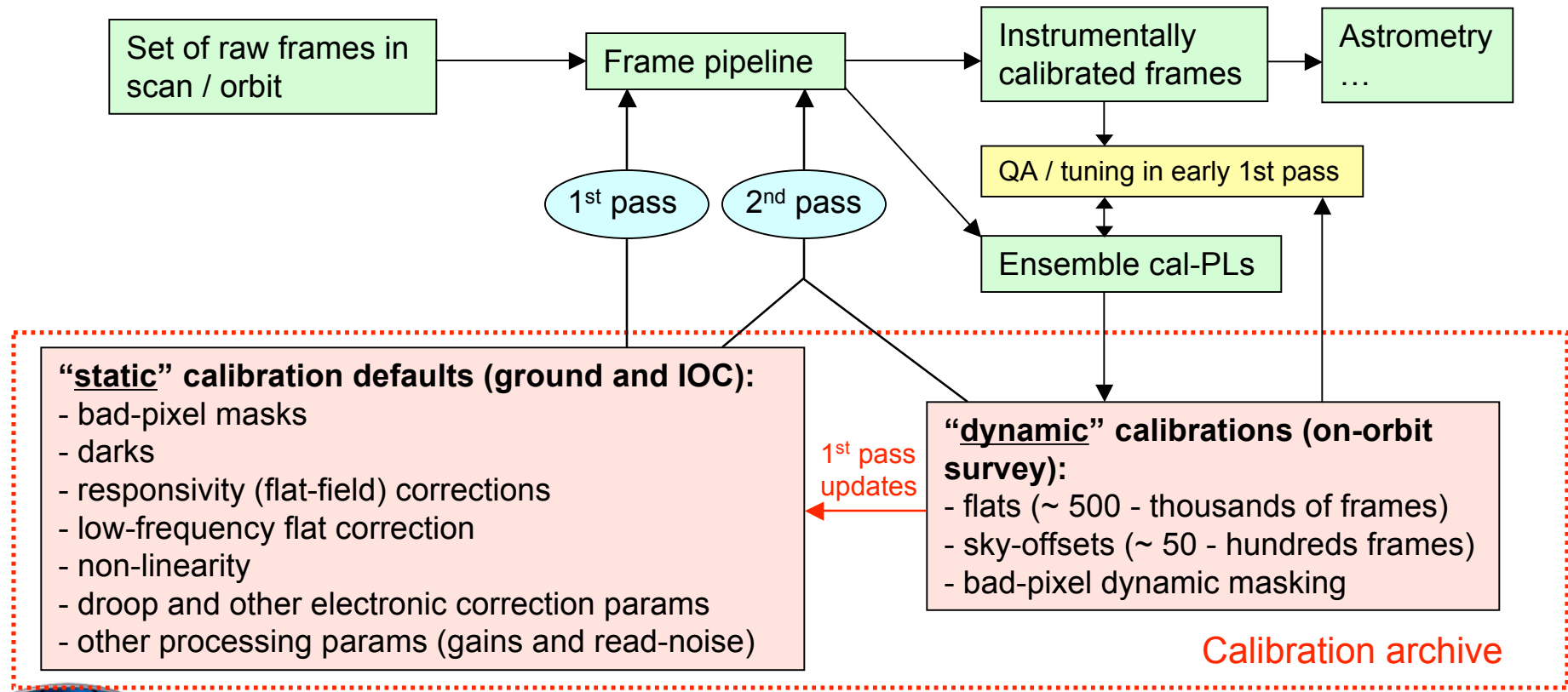


Calibration Flow



Plan is to have two processing phases:

- **1st pass:** use ground and updated calibrations from IOC; generate dynamic on-orbit calibrations and optimize windows/parameters (desired accuracy, anneals, SAA passages, stability, transients, bright source avoidance etc.):
 - Apply asynchronously to frame processing on experimental basis, or, if leads to “better” product.
 - Update static defaults with “better” calibrations from dynamic processing (e.g., super-flats, masks).
- **2nd pass (post flight):** expect all frame/scan intervals to be appropriately “calibration matched” prior to reprocessing





Mask Initialization / Updating



- A processing bit-mask is initialized using a mask from ground characterization. This flags pixels with:
 - excessive dark current;
 - excessive read noise;
 - low and high responsivity (dead and hot pixels);
 - reach and stay saturated in their A/D ramps during a nominal exposure;
 - strong inter-pixel capacitance (IPC) - usually the nearest neighbors to hot pixels.
- The mask will also be updated for conditions flagged by on-board DEB processing and recorded in actual down-linked frames: e.g., ramp saturation, broken pixels, DEB -> MUB transfer loses, and overflow.
- Masks are further updated dynamically downstream to record:
 - pixels that cannot be calibrated (e.g., dark subtracted, linearized, flattended...);
 - new (transient) low/high responsive pixels using stacking analyses from the sky-offset estimation step;
 - more “bad” pixels subject to IPC effects and energy leakage from photons hitting dead pixels/regions;
- These frame-pixel status masks will give us flexibility on which pixels to omit from the multi-frame processing steps - e.g, co-addition.



Mask Bit Definitions

- Pixel status information on: “static” bad pixels flagged *a priori* on the ground; new/transient bad pixels flagged dynamically using on-orbit data; and unreliable calibrations will be stored in a 32-bit image mask.
- Every image frame processed by the frame pipeline will have an associated mask.

Bit # Condition

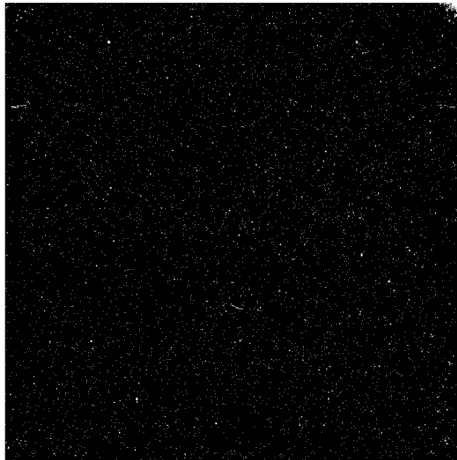
0	masked from ground characterization: excessive dark current	14	saturated in sample read 5 (downlink value = 32757)
1	masked from ground characterization: excessive read noise	15	saturated in sample read 6 (downlink value = 32758)
2	masked from ground characterization: dead pixel	16	saturated in sample read 7 (downlink value = 32759)
3	masked from ground characterization: low responsivity	17	saturated in sample read 8 (downlink value = 32760)
4	masked from ground characterization: high responsivity (hot)	18	saturated in sample read 8 (downlink value = 32761)
5	masked from ground characterization: neighbor affected by IPC	19	reserved
6	reserved	20	reserved
7	reserved	21	new/transient bad pixel from dynamic masking
8	DEB -> MUB transfer loss (downlink pixel value = 32766)	22	flat-field not applied or unreliable
9	broken pixel (intrinsically negative SUR, downlink value = 32767)	23	sky-offset (illumination-correction) not applied/unreliable
10	saturated in sample read 1 (downlink value = 32753)	24	contains optical artifact: diffraction spike
11	saturated in sample read 2 (downlink value = 32754)	25	contains optical artifact: latent
12	saturated in sample read 3 (downlink value = 32755)	26	contains optical artifact: ghost or glint
13	saturated in sample read 4 (downlink value = 32756)	27	contains cosmic-ray hit or outlier that cannot be classified
		bits 28 - 31:	reserved



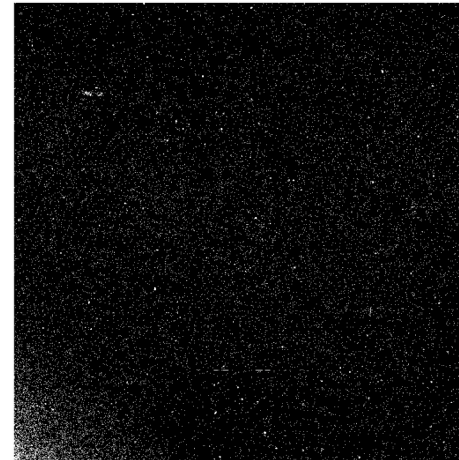
Flight array bad-pix masks (as of Oct 2007)



These assume the flagging criteria on page 8 (white dot => bad pixel) derived from ground testing of proposed flight arrays:



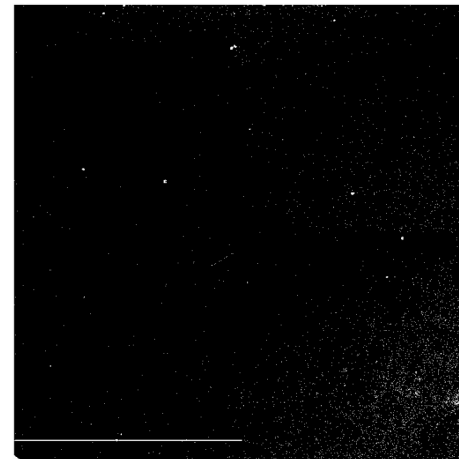
Band 1 (fpa136):
%bad pix = 1.2%



Band 2 (fpa147):
%bad pix = 3.24%



Band 3 (fpa26):
%bad pix = 0.15%



Band 4 (fpa29):
%bad pix = 0.87%





Bias / Offset Subtraction



- The active region of each array is 1016×1016 pixels. This is surrounded by a 4 pixel-wide border called the “reference pixel region”.
- The reference pixels are not connected to the indium layer and do not generate photo-electrons (e.g., compare to ‘overscan’ region of a CCD).
- For bands 1 & 2 (HgCdTe arrays), the reference pixels can be used to remove time-varying DC-offsets across each read-out channel in the active region.
 - This uses a row/column moving averaging algorithm provided by Teledyne. It will be further tuned when arrays are connected to flight electronics.
- For bands 3 & 4 (Si:As arrays), it is not yet known how useful the reference pixels will be for removing DC offsets.
 - In testing, an effect known as “banding” was seen where distinct blocks of offsets were seen that started and stopped on clusters of bad pixels.
 - These were not related to offsets represented by the reference pixels.
 - Not yet fully characterized.



Droop & Electronic Artifacts



- Droop was seen in some of the *Spitzer* arrays (most notably MIPS Si:As).
- Droop manifests itself as an erroneous signal added to the output of a pixel that depends on the total counts on the array - a global coupling between the readout channels or amplifiers.
- 2nd order effects were also seen in the *Spitzer* arrays. E.g., where the output from a pixel depends on the total counts from all other pixels in its row or column.
 - This will impact the degree of repeatability in source photometry with location on an array.
- There are plans to search for and characterize droop in all arrays on the ground, and also possibly measure/validate it in flight.
 - Parameterized in terms of a proportionality coefficient between output signal from a pixel and total counts on the array and may be pixel dependent.
 - Since electronic effect, total counts from saturated signals need to be estimated to avoid underestimation
- Other electronic artifacts will be searched for and characterized:
 - Inter-pixel capacitance (IPC) and crosstalk (including inter-band).
 - Note: IPC will artificially broaden PRFs, reduce image quality and sensitivity.
 - Readout-channel dependent patterns and drifts (e.g., “banding” for bands 3 and 4).





Dark Calibration



- Darks and their stability for all bands will be measured/characterized on the ground.
- In flight:
 - Bands 1 & 2: it may be possible to measure darks with cover-on during IOC.
 - Bands 3 & 4: are predicted to saturate with cover-on
⇒ must rely on ground darks!
- Incorrect dark estimates will impact flat-field estimates (more later).
- A crude way to monitor average (long-term) dark levels and stability is to use the relative change in backgrounds along a WISE orbit and comparing to DIRBE predictions:
 - E.g., for observed backgrounds at a pole and equator of B_{pole}^{obs} , B_{eq}^{obs} respectively, and assuming the dark/bias offset D over an array is \sim constant over 1/4 of an orbit, we expect:

$$\frac{B_{pole}^{obs} - D}{B_{eq}^{obs} - D} \approx \frac{B_{pole}^{DIRBE}}{B_{eq}^{DIRBE}}$$

- But we can do better and monitor changes in bias and dark structure on the pixel scale by computing a sky median every N frames along every orbit - the essence of the “sky-offset” calibration step...

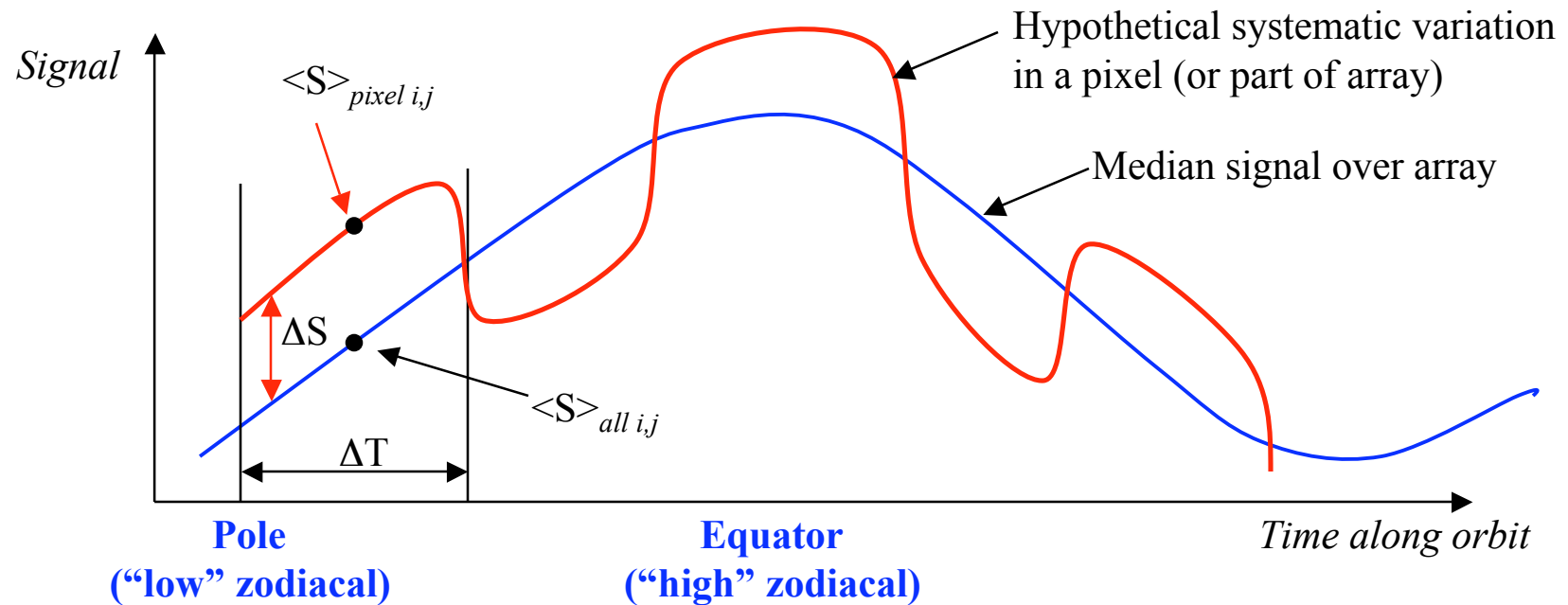


Sky-offset ('illumination') Correction

- Short-term variations in bias, dark (and gain) structure over an array will not be captured by ground (or long term) calibrations.
- These will manifest as instrumental residuals and impact photometric accuracy.
- These can be corrected by computing a median of ~50 - 100 consecutive frames within a moving block window, zero-normalizing to the global median, and subtracting this from all frames in that window.
 - At least this number of frames will be needed to reliably filter out sources;
 - A window that's too big may miss the short-term instrumental variations;
 - Assumption is that the bias/dark structure is constant over the window span.
- Sky-offset corrections will be computed autonomously by saving intermediate products from the frame pipeline: frames that have been dark subtracted, linearized and flattened.
- This pipeline thread will also dynamically mask and propagate out-of-range pixels (transient low/high responsive pixels) as well as new bad pixels from the stacking statistics.
- Above method was shown to reduce variance in source photometry in 2MASS.



Sky-offset correction schematic



ΔT = timescale of possible systematic variation

$\langle S \rangle_{\text{pixel } i,j}$ = median or mean signal in single pixel i,j over stack of N frames in ΔT

$\langle S \rangle_{\text{all } i,j}$ = median or mean signal over all pixels and N frames in ΔT

Sky - offset correction: $\Delta S_{i,j,\Delta T} = \langle S \rangle_{\text{pixel } i,j} - \langle S \rangle_{\text{all } i,j}$

- Number of frames must satisfy: $N_{\min} \leq N \leq N_{\Delta T}$, where N_{\min} is minimum so can filter out stars
- If $N_{\Delta T} < N_{\min}$ (fast instrumental variations), then method can't be used
- Plan is to determine frame windows N_{\min} and $N_{\Delta T}$ early in mission

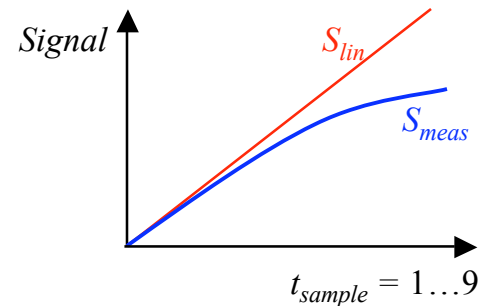




Non-linearity Correction



- Will first be characterized and measured on the ground for every pixel.
- Simple quadratic model fit to ramp data: $S_{lin} = c_1 S_{meas} + c_2 S_{meas}^2$



- Will then be measured and validated in-flight using an experiment in IOC:
 - Based on toggling “sample up the ramp” coefficients over several orbits to control frame exposure times, then combining measurements of the same stars and fitting non-linearity curves.
 - Won’t be able to measure non-linear response on a per pixel basis - only over a coarse grid to be determined by the density of usable stars.
- Note: WISE will downlink a linear combination of ramp samples (effective slope), therefore we must convert.
- We must ensure to sample the full dynamic range in the A/D up to saturation.
- Watch out for any “hook-like” effects in the linear, low part of a ramp (already seen in some test data).
- Characterization will also assess stability, dependencies on temperature (e.g., anneals), uncertainties.





Flat-fielding



- Flats will be first obtained on the ground, then in-flight during survey operations from observations of the zodiacal background.
- Dependencies on temperature (anneals) will be characterized.

From calibration plan, need to combine following number of frames:

- Bands 1 & 2: multiple orbits ($>\sim 15$ orbits \Rightarrow thousands of frames) will give flats to an accuracy of 0.2 - 1%. Background is low and need enough signal to fill wells.
- Bands 3 & 4: at least one orbit worth ($>\sim 520$ frames) will give flats to accuracy $<\sim 0.1\%$
- Flat-fielding in bands 3 & 4 needs to be more accurate due to high backgrounds, i.e., an erroneous flat \Rightarrow bad background estimate \Rightarrow bad aperture photometry since “larger” (uncertain) background is subtracted.





Flat-fielding continued..



- As mentioned earlier, flat-field accuracy is also determined by knowledge of the dark D , since for a pixel i with signal S_i :

$$F_i = \frac{\langle L_i(S_i - D_i) \rangle_{stack\ for\ pix\ i}}{\langle L_i(S_i - D_i) \rangle_{all\ frames,\ all\ i}}$$

- L_i = non-linearity correction factor, also implicitly depends on knowledge of the dark.
- Pixel-to-pixel responsivity variations are *underestimated* if D is also *underestimated*.
- Sky flats will be generated dynamically by saving intermediate products from the frame pipeline: specifically dark subtracted and linearized frames.
 - Depending on detector performance, transients, behavior after anneals etc, a decision will be made on whether to apply these dynamic calibrations immediately to the science frames in hand. If so, this will incur a lag of up to 24 hours between calibration creation and their application.
 - Note: all science data frames will be appropriately calibration matched in the 2nd (post-flight) processing pass.
- If detectors are stable enough, we may consider creating super-flats by combining frames from many orbits (more than what is called for to meet sensitivity requirements).





Flat-fielding continued..



- Also, we will derive “low-frequency” correction maps for the flats
 - These characterize variations from imperfections when light goes through the entire WISE optical train and is incident from different directions; i.e., position dependent throughput.
 - A task for IOC: can be derived by placing the same star on different portions of an array and measuring relative changes in its brightness.
 - It is expected that these corrections will be made once and applicable throughout the mission.
 - Low-frequency correction maps will be applied to the high-frequency flats before they’re archived.
- Other flat-fielding calibration quirks learnt from other instruments (e.g., on *Spitzer*):
 - Dependence of band-pass (relative spectral response) with position on array due to differing angles of incidence on filters.
 - Dependence of flat-field corrections on source color - e.g., zodiacal background is red in bands W1, W2. Sky-flats will only be applicable to sources of the same color.
 - These will be characterized and their impact on relative source photometry assessed.
 - Reminder: requirement for relative photometric accuracy is 7% (on SNR>100 point sources). This allows enough leverage to account for uncharacterized/unforeseen systematics.





Instrumental Calibration Summary



- In a nutshell, the full process entails determining pixel signals S_{cal} corrected for instrumental signatures from raw signals S_{raw} according to:

$$S_{cal} = \frac{L_S(S_{raw} - B - D - E_S)}{F} - \Delta S$$

Diagram illustrating the instrumental calibration equation with annotations:

- L_S : Linearity correction factor
- B : Bias/offset from reference pixels
- D : Dark
- E_S : Electronic droop
- F : Responsivity (flat-fielding)
- ΔS : Sky-offset (illum) correction

- We will include any new corrections found in upcoming characterization/testing.
- In addition, uncertainties in the final calibrated signals are also determined. These are initiated by an error model, then propagated and updated by all steps that modify pixel values using independent (stochastic) calibration products.
- Error model: Based on a Poisson and read-noise model that allows for correlated errors in Sample Up the Ramp (SUR) data. Methodology was successfully used on *Spitzer*-MIPS data.
- Error model uncertainties will be validated and updated (if necessary) using repeatability.



Pre-flight/IOC Calibration Receivables

- Below is a summary of calibration products to support processing above.
- Excludes optical source-artifact characterization (e.g., glints, ghosts, latents.); *PSF*; distortion.
- Specifications for formats, content and suggested algorithms are outlined in:
http://web.ipac.caltech.edu/staff/fmasci/home/wise/GroundCalDeliv_specs_v1.0.pdf

product	ground	IOC (yes/no)	survey mode
Darks	yes - SDL, Ames	yes - only W1, W2 with cover on as check	no
Flats	yes - SDL	yes - cover off (tune)	yes (dynamic)
Low-frequency flats	no	yes - cover off	no
Non-linearity	yes - SDL	yes - cover off (check)	no
Saturation limits	yes - SDL	yes - cover off (check)	yes (monitor)
Gain and read-noise maps	yes - SDL	yes (gain only)	maybe monitor
Droop coefficients	yes - SDL	yes - cover off (check)	maybe monitor
Bad-pixel masks	yes - SDL	yes - cover on (update)	yes (dynamic)
Sky-offset (illumcor)	no	yes - cover off (tune)	yes (dynamic)

Development Schedule

- **Version 0 - August 2007:** *prototype and dataflow infrastructure*
 - Initial version that uses mock input calibrations complete
 - Specifications for ground-based calibration deliverables w/ suggested algorithms
- **Version 1 - May 2008:** *input test / simulation data with signatures from ground characterization*
 - Complete pipeline modules and core pipeline thread: *offset corrections using ref pixels for bands 3/4 (banding effects?); droop and other electronic artifacts, non-linearity*
 - Pipeline threads for creating on-orbit calibrations: *responsivity and sky-offset corrections*
 - Ground (static) calibration products generated (see earlier slides)
 - Calibration directory structure for static and dynamic products in place and functional
 - Create test suite: obtain simulation data with instrumental signatures included and compare calibrated frames from pipeline with truths
- **Version 2 - November 2008:** *mission scenario testing using simulations and Spitzer data*
 - QA diagnostics and metrics for level-1 image products implemented (as per QA plan).
 - Check uncertainty estimation/propagation (via error model) using simulated SUR data
 - Required metadata and DB infrastructure for creating/querying dynamic and static calibration products defined and in place
 - Level-1 FITS image header metadata defined (for archival)



Development Schedule



Instrument Calibration

- **Version 3 - June 2009:** *operations readiness testing, launch, IOC*
 - Optimization of core modules
 - Final Product Generator for Level-1 image products and metadata
 - Adopt existing or write new software to derive ancillary calibrations from IOC, e.g: *linearity, droop, low-frequency responsivity maps*
- **Version 3.5 - December 2009:** *tune-up pipelines/modules according to on-orbit performance*
 - Input parameter tuning and feedback from QA: check and/or update calibrations derived from IOC, update bad-pixel masks and optimize intervals for on-orbit calibration products
 - Further optimization (if needed)
 - Start to distill documentation/analysis pages into Explanatory Supplement
- **Version 4 - September 2010:** *reprocessing (final processing pass)*
 - Tune up/optimize all parameters for final processing pass
 - Ensure all frames/scans are appropriately matched to ‘best’ calibration products from either first pass processing or re-derived. Account for anneals and other unforeseen transients
 - Ultimate goal: select/match the calibration sets that give the best photometric repeatability throughout the mission





Concerns/Issues



- Thoroughness of ground characterization/testing under flight-like environment and electronics, e.g., before/after anneals
- Timeliness of analysis, and derivation of pre-flight and IOC calibration products
- Detectors don't perform in flight as expected from ground testing
- New instrumental signatures, transients, systematics that cannot be forecast or modeled
 - E.g., bias/dark/gain structure varies on a time scale that is too short to estimate and correct using sky-offset subtraction procedure
- Science data losses, especially during anneals. Impact from image persistence (latents).
- Recovery after anneals, SAA passages, bright saturating sources

