# Instrumental Calibration

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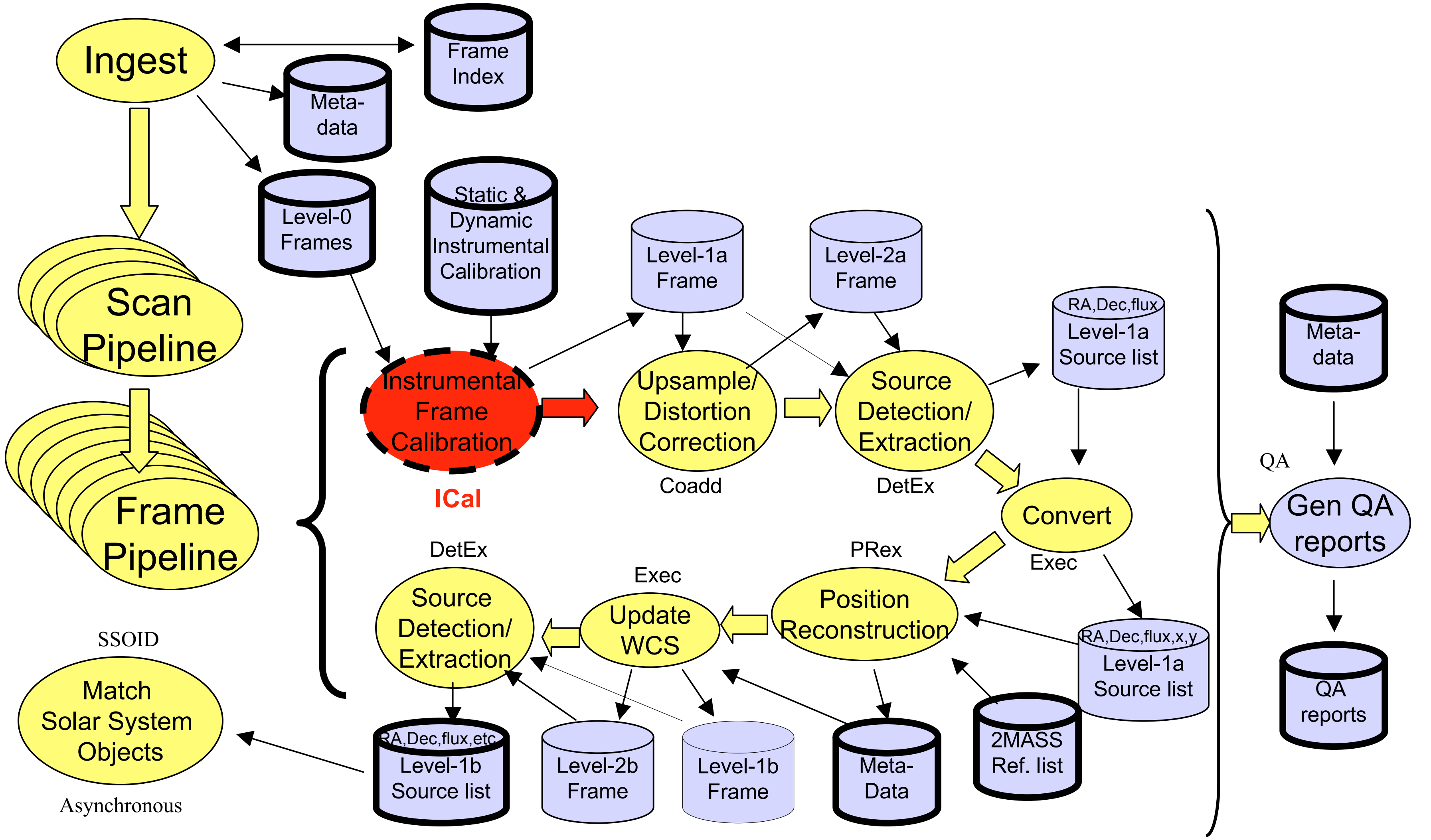
# WSDS Scan/Frame Pipeline





# 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.

# 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-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



**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**

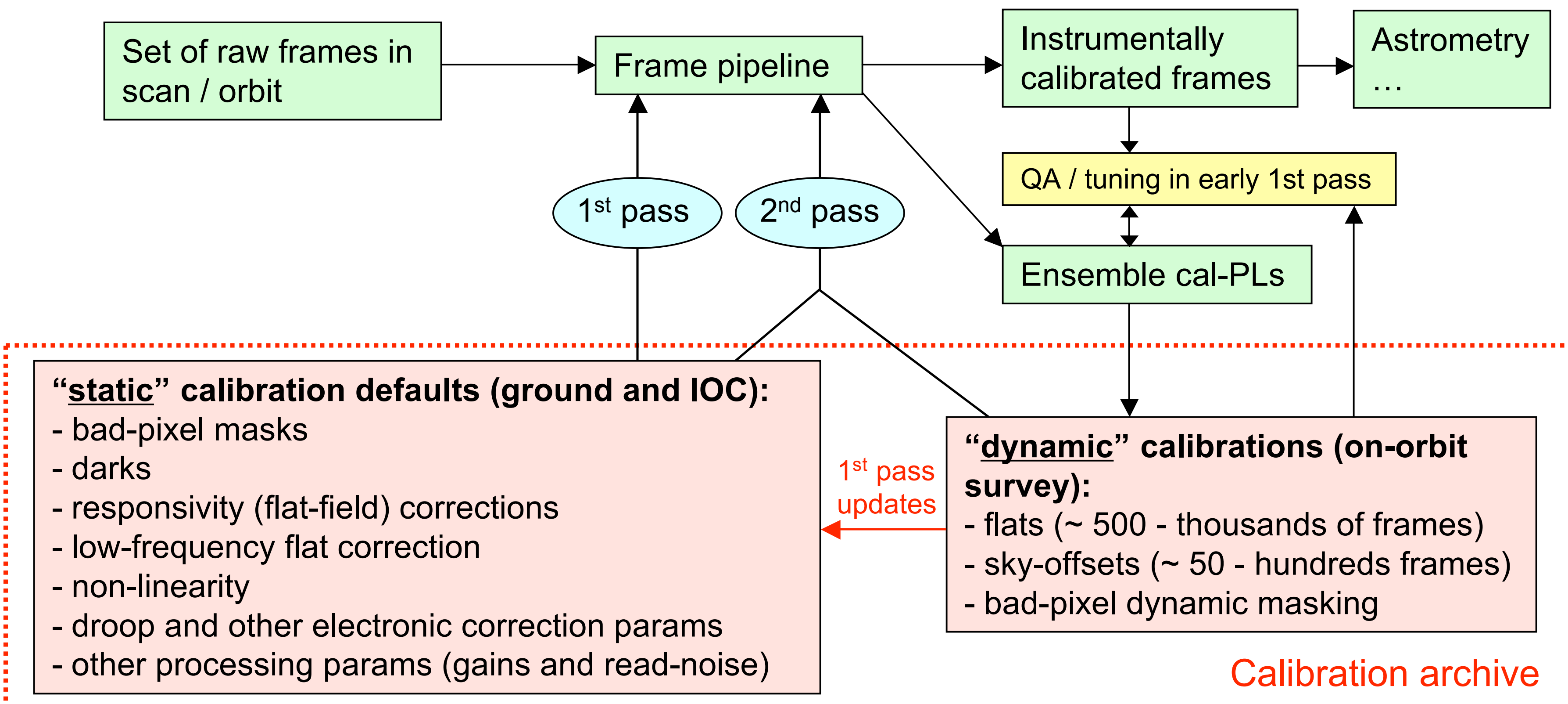
**OUTPUTS:**
- instrumentally calibrated FITS frame
- bit-mask storing processing status
- uncertainty image frame
- QA diagnostics

# Calibration Flow



**Baseline plan for the 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



# 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:

Bias/offset from reference pixels

Dark

Linearity correction factor

Electronic droop

Sky-offset (illum) correction

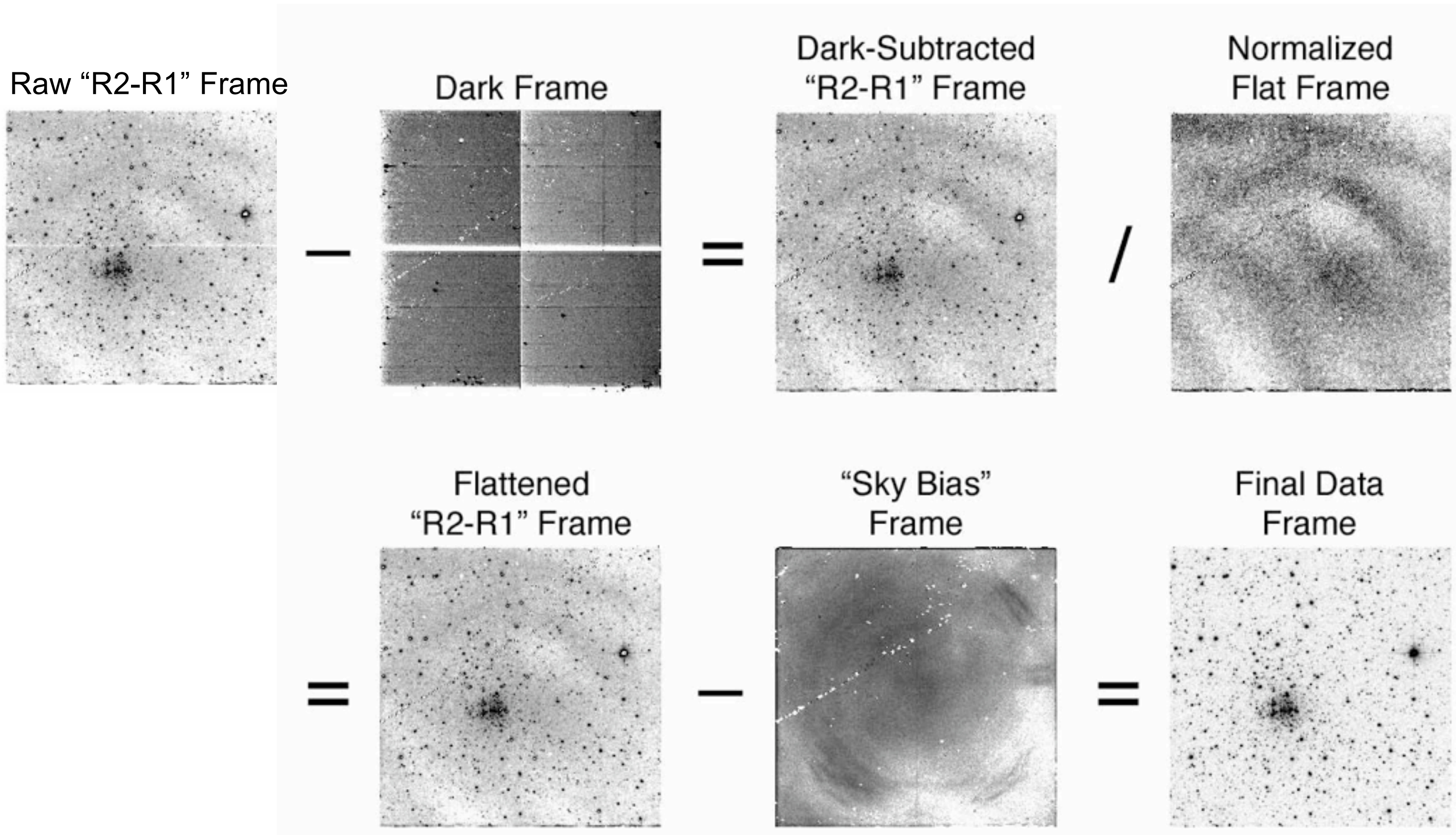
$$S_{cal} = \frac{L_S\left(S_{raw} - B - D - E_S\right)}{F} - \Delta S$$

Responsivity (flat-fielding)

- 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.

# E.g. from 2MASS processing





# 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, physically “broken” pixels, DEB to 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 masks will give us flexibility on which pixels to omit from the multi-frame processing steps - e.g, co-addition.

# Bit-Mask Definitions



- Pixel status information will be stored in a 32-bit image mask.
- Every image frame processed by the frame pipeline will have an associated mask.

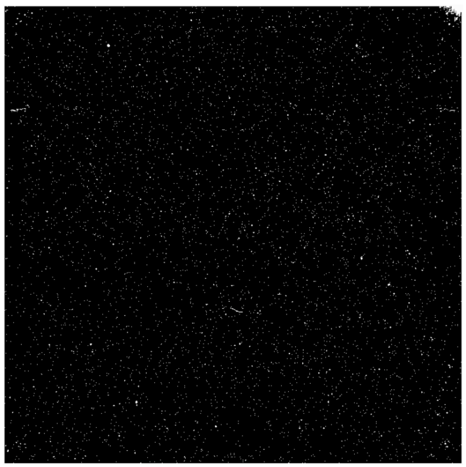
| Bit # | Condition |
|---|---|
| 0 | masked from ground characterization: excessive dark current |
| 1 | masked from ground characterization: excessive read noise |
| 2 | masked from ground characterization: dead pixel |
| 3 | masked from ground characterization: low responsivity |
| 4 | masked from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

bits 28 - 31: reserved

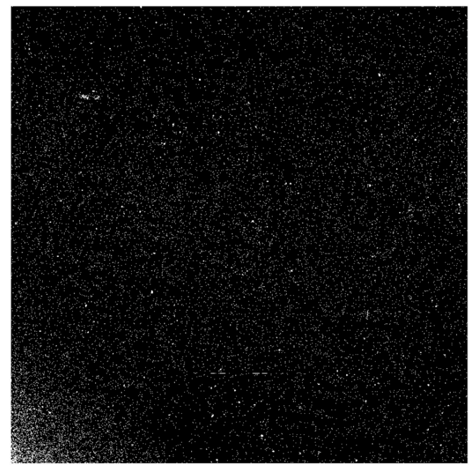
# Flight array bad-pix masks (as of Oct 2007)



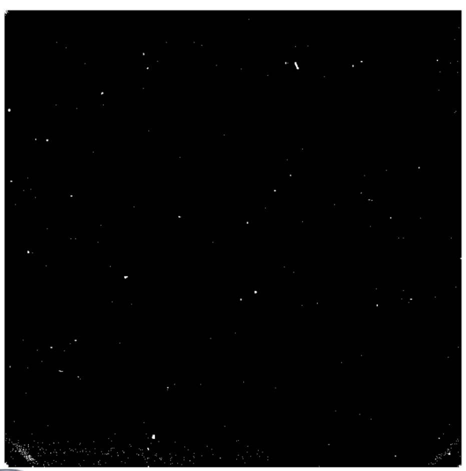
These assume the flagging criteria on page 8 (white dot => bad pixel) derived from ground testing of proposed flight arrays:



**Band 1 (fpa136):**
%bad pix ~ 1.2%



**Band 2 (fpa147):**
%bad pix ~ 3.24%



**Band 3 (fpa26):**
%bad pix ~ 0.15%

**Band 4 (fpa37):**
%bad pix ~ 0.25%

# 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 during ground characterization at SDL.
- 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 (coupling 'constant') between output signal from a pixel and total counts on the array and may be pixel dependent.
  - This erroneous signal is then subtracted from each pixel - heritage s/w from *Spitzer* will be used.
  - 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.
- WISE does not have a shutter to give us darks.
- 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.

    ⇒ thus, must rely on ground darks!
- Uncharacterized variations in the dark levels will impact flat-field estimates (more later).
- With incomplete knowledge of the dark levels, we can however 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 (PTO)…

# 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.

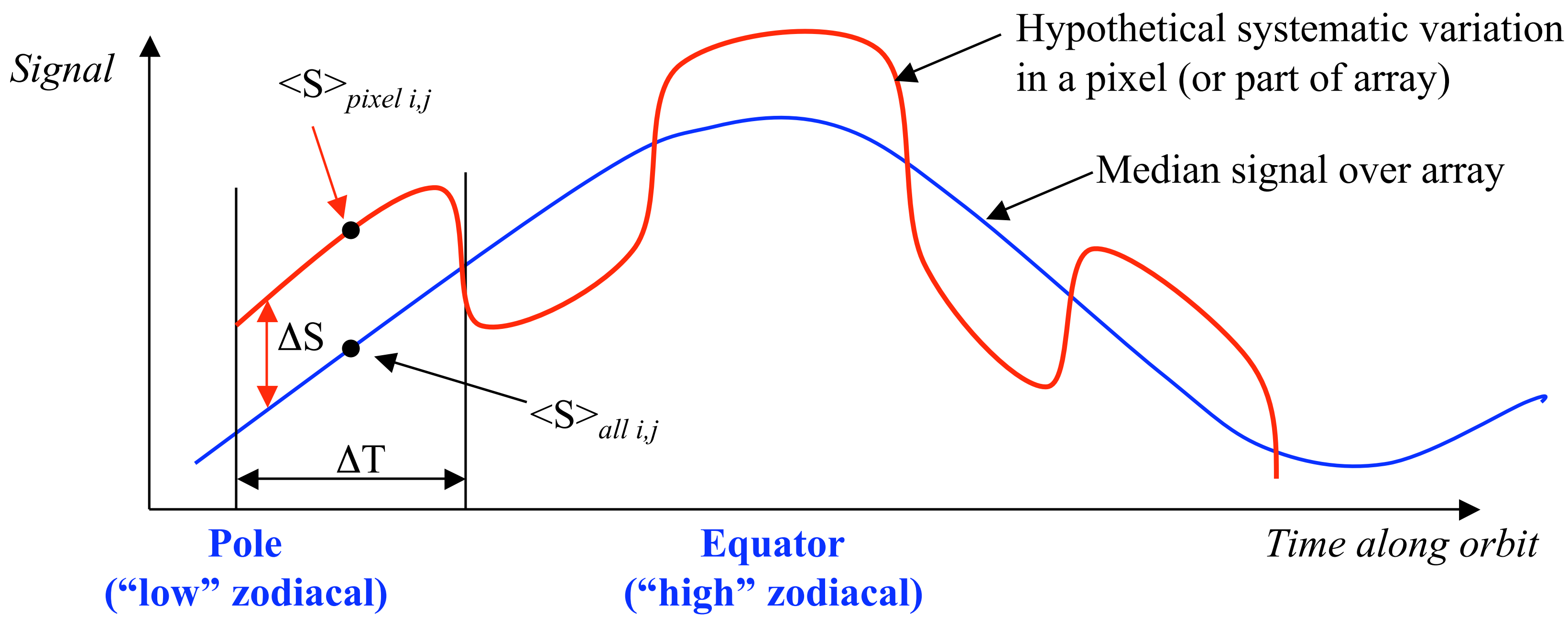
- Sky-offset corrections will be computed autonomously by saving intermediate products from the frame pipeline: frames that have been dark subtracted, linearized and flattened.

- 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






$\Delta T$ = timescale of possible systematic variation

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

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

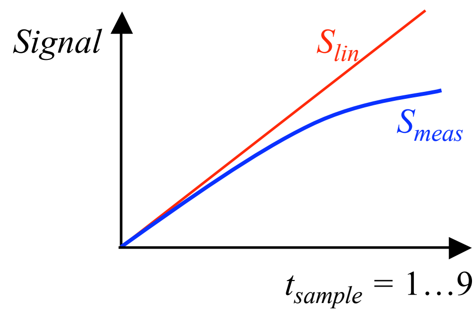
Sky-offset correction: $\Delta S_{i,j,\Delta T} = \langle S \rangle_{pixel\ i,j} - \langle S \rangle_{all\ i,j}$

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

# Non-linearity Correction



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




- 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.

- Ground tests at SDL will 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).

# Pixel Responsivity Correction (flat-fielding)



- Flats will first be obtained on the ground, then in-flight during survey operations from the *change* in the zodiacal background light.
  - Zodi will vary by ~ 40-50% in bands 1 and 2, and ~30% in bands 3 and 4 from ecliptic equator to pole.
  - Will involve median combining a high and low zodi batch separately, differencing, then normalizing.
  - Method helps mitigate incomplete knowledge of the *absolute* dark level, but not necessarily short-term variations about this level.
  - Successfully used on 2MASS for deriving flats from the twilight sky.

- Dependencies on temperature will be characterized on the ground to determine impact of anneals on pixel responsivity.

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

- <u>Bands 1 & 2</u>: multiple orbits (>~ 15 orbits => thousands of frames) will give flats to an accuracy of 0.2 - 1%. Background is low and need enough signal to fill wells.
- <u>Bands 3 & 4</u>: at least one orbit worth (>~520 frames) will give flats to accuracy <~0.1%

- Flat-fielding in bands 3 & 4 needs to be more accurate due to <u>high</u> backgrounds, i.e., an erroneous flat => bad background estimate => bad aperture photometry since a “larger” (uncertain) background is subtracted.

# Flat-fielding continued..



- 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 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.
- Reminder: all science data frames will be appropriately calibration matched in the 2nd (post-flight) processing pass.
- If detectors are stable enough, we may also 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 using on-orbit data.
  - These characterize variations from imperfections when light goes through the entire WISE optical train and is incident from different directions; i.e., calibration of system throughput.
  - Can be derived by tracking the same star on different portions of an array and measuring relative changes in its brightness. Will be done in IOC.
  - 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/used.

- Other flat-fielding calibration quirks learned from other instruments (e.g., *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.

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

# Tools for IOC Analyses



Some of these already written to support other missions (e.g., 2MASS, *Spitzer*)

- Non-linearity estimation from on-orbit star-mapping experiment
- Low-frequency responsivity maps
- Droop coefficient determination
- Optimization of windows (numbers of frames) for sky-offset computation, and tracking of instrumental variations
- Cover-on darks for bands 1 and 2

# Summary from Peer Review



- Calibration Plan peer review held September 28, 2007 at IPAC.
- Main conclusions, discussions, recommendations and suggestions:
  - Band-to-band cross crosstalk characterization, and near-field stray light tests.
  - Ice buildup on optical surfaces - band-1 filter in particular. Use spectra of astronomical sources to characterize/monitor.
  - Determination of darks, flats as accurately as possible in ground testing with exactly same readout patterns as in flight.
  - Stability of calibrations versus changes in temperature in the warm electronics - collect data during thermal vac. testing.
  - What kind/how much droop will saturated sources cause?
  - Measure spectral response across arrays to see if there's significant variation.
  - Consider adding to receivables list: bright source artifacts such as muxbleed and column pulldown.
  - Will the entire ramp saturate in bands 3 and 4 in IOC cover-on data?
  - Realize there may be a difference between point-source and extended source flats.

# Development Schedule



- **Version 0 - 8/30/2007:** *prototype and dataflow infrastructure*
  - Initial version that uses mock input calibrations complete
  - Specifications for ground-based calibration deliverables w/ suggested algorithms

- **Version 1 - 5/31/2008:** *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 - 11/30/2008:** *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



- **Version 3 - 6/30/2009:** *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 of ancillary calibrations from IOC, e.g: *linearity, droop, low-frequency responsivity maps*

- **Version 3.5 - 12/30/2009:** *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 - 9/20/2010:** *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



- 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 accumulated image persistence (latents).
- Recovery after anneals, SAA passages, bright saturating sources