Frame Co-addition

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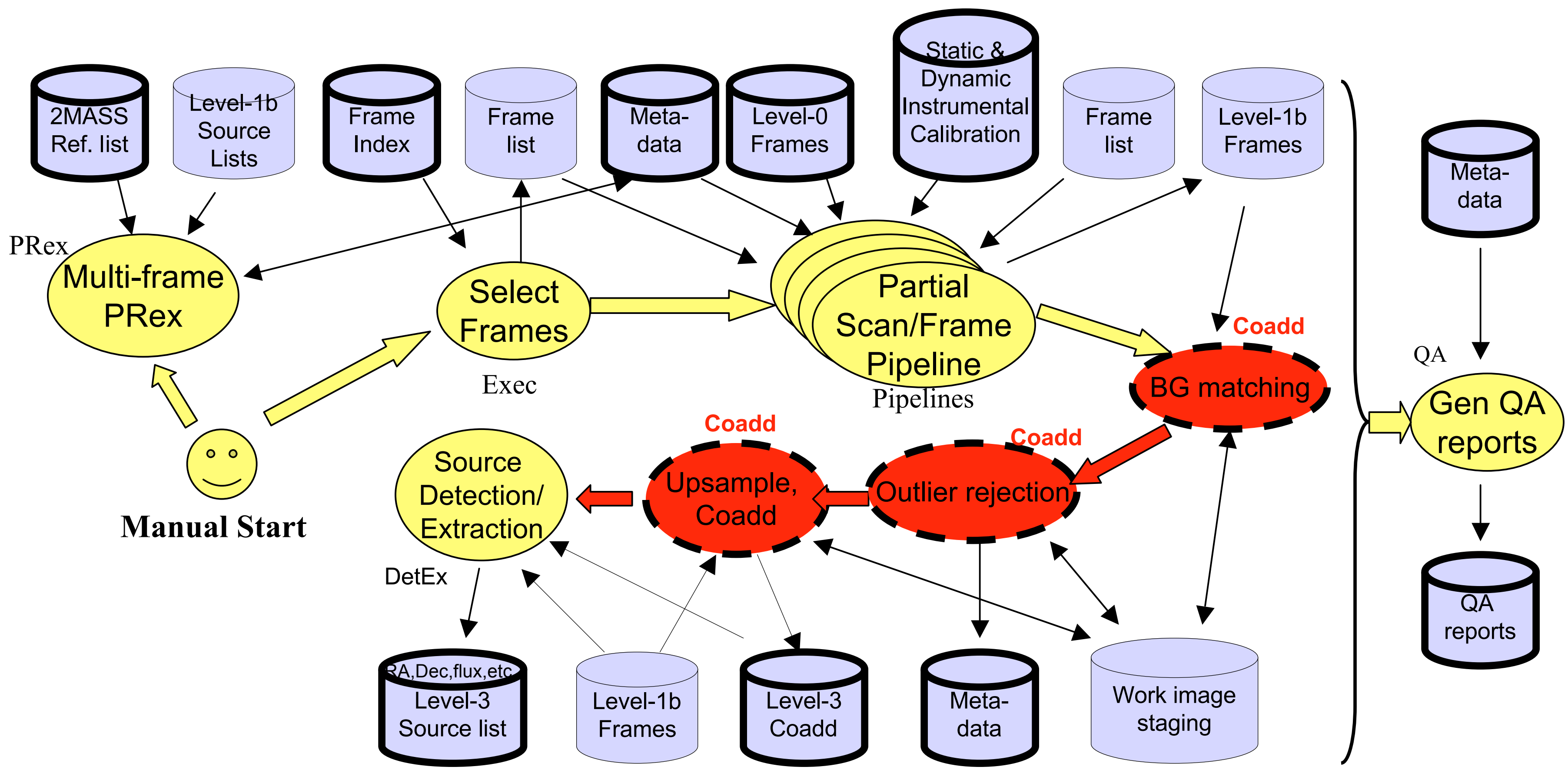
WSDS Multi-frame Pipeline

Frame Co-addition



Requirements (Level 4)

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

- **L4WSDC-001:** The WSDC shall produce a digital Image Atlas that combines multiple survey exposures at each position on the sky.
- **L4WSDC-004:** The WSDC shall release the *final* WISE digital Image Atlas, Source Catalog and Explanatory Supplement within 17 months of the end of on-orbit data collection.
- **L4WSDC-005:** The WSDC shall generate a *preliminary* digital Image Atlas using data from the first 50% of the sky that is surveyed.
- **L4WSDC-008:** The WSDC shall release the *preliminary* WISE Image Atlas, Source Catalog and Explanatory Supplement within 6 months of the end of on-orbit data collection.
- **L4WSDC-022:** The photometric calibration of the final WISE Image Atlas shall be tied to the photometric calibration of the final WISE Source Catalog.
- **L4WSDC-023:** The WSDC shall make all WISE image data available in accordance to the Flexible Image Transport (FITS) astronomical data standard.
- **L4WSDC-021:** The images in the final WISE Image Atlas shall be re-sampled to a common pixel grid at all wavelengths.
- **L4WSDC-078:** The WISE science data products shall use the International Celestial Reference System (ICRS) to describe the positions and motions of celestial bodies. WISE astrometry shall be mapped into the ICRS using the 2MASS All-Sky Point Source Catalog as the primary astrometric reference.

Requirements continued..

- **L4WSDC-047:** The WSDS Pipeline processing shall combine multiple image frames covering each point on the sky to form the Atlas Images, and construct coverage maps that encode the number of image frames contributing to each pixel of the Atlas Images.
- **L4WSDC-026:** The WSDC shall generate and archive coverage maps that show the number of independent observations that go into each pixel of the Image Atlas images in each band. The coverage numbers shall take into account focal plan coverage and losses due to poor data quality, low responsivity and/or high noise masked pixels, and pixels lost because of cosmic rays and other transient events.
- **L4WSDC-084:** The WISE Image Atlas shall be constructed by combining all available science images covering the sky. This does not include image pixels rejected because of low responsivity, high dark current or read noise, transient behavior such as charged particle impacts, or scattered light due to moon proximity.
- **L4WSDC-051:** The WSDC shall make the WISE catalog and image products available to the community via the internet through appropriate web-based tools.
- **L4WSDC-053:** The WSDC shall make the Image Atlas and Catalog products accessible to the astronomical community in collaboration with the NASA/IPAC Infrared Science Archive (IRSA) to ensure long-term availability beyond the end WISE missions operations and data processing phase, and to insure interoperability with other NASA mission archives.

Requirements continued..

- **L4WSDC-086:** The web-based interface to the WISE Image Atlas shall allow the user to view and retrieve an image in any of the four WISE bands with any specified center (tangent point) and any size up to at least $1° \times 1°$.
- **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-041:** As a goal, the WSDC shall combine image data from multiple orbits and extract sources from the combined images at intervals of no shorter than 3 days and no longer than 30 days to generate a temporary, intermediate combined image archive and source database for the purpose of science data quality assessment by the WISE Science Team and WSDC.
- **L4WSDC-080:** The final WISE Source Catalog shall have greater than 99.9% reliability for sources detected in at least one band with SNR>20, where the noise includes flux errors due to zodiacal foreground emission, instrumental effects, source photon statistics, and neighboring sources. This requirement shall not apply to sources that are superimposed on an identified artifact. *=> Relates to reliability of outlier detection and flagging.*
- **L4WSDC-063:** The WSDC shall work with the WISE Science Team to validate that the Image Atlas and Source Catalog satisfy WISE science requirements prior to their release.

Deliverables (Co-add products)

- Digital Image Atlas will consist of co-adds that combine multiple frame exposures within pre-defined regions on the sky in each of the four bands: 3.3, 4.7, 12 and 23μm

- For each band, the plan is to have three products (all same dimensions):
  - Main intensity co-add image
  - Associated depth-of-coverage map indicating effectively the number of unmasked (good) pixel contributions
  - Uncertainty co-add image that contains the 1-σ error estimate in the co-add signal for every pixel

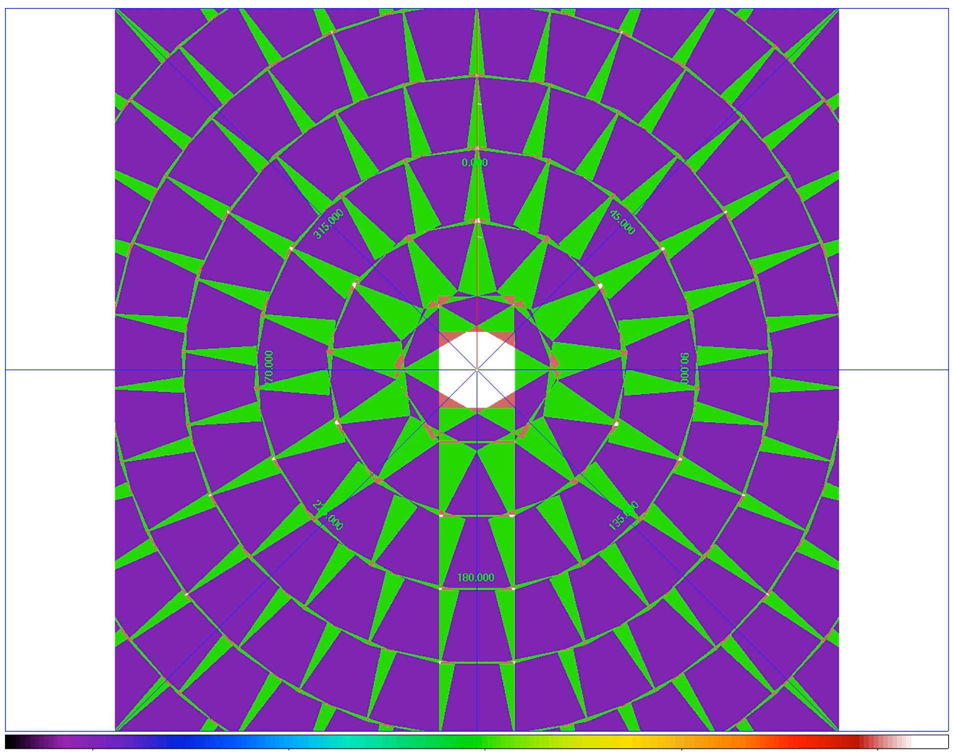
- Explanatory supplement:
  - Methodology
  - Recipes on using products (uncertainties and coverage maps) to perform source photometry

- Given 4 bands and 3 co-add products per band, expect Atlas Image archive to be ~28 TB and 15 TB (uncompressed) for pixel scales of 1 and 1.375 arcsec/pixel respectively.
  - Assumes 4k × 4k pixel tiles arranged along iso-declination bands with some minimum overlap (PTO).

Tiling Geometry

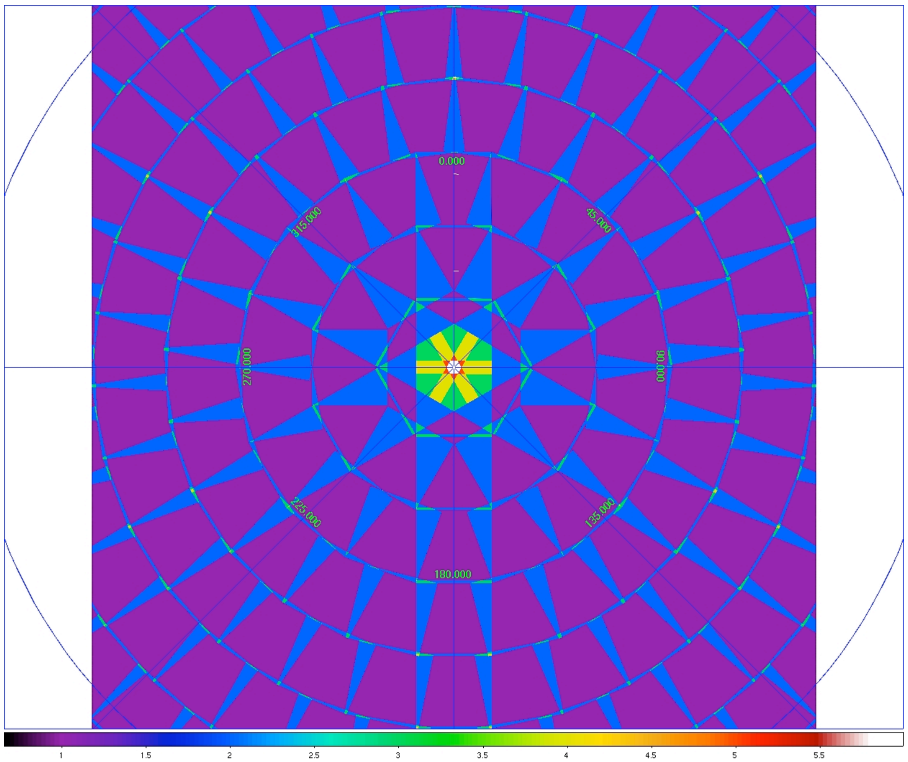
Below are schematics of the Atlas Image footprints (tiles) at an equatorial pole.

- **<u>Case 1:</u> 4096 × 4096 pixels at 1 arcsec/pixel:**
  - Linear tile sizes: ~1.137 degrees;
  - Position angles of all image tiles are zero;
  - A *minimum* linear overlap between any two adjacent tiles of 2 arcmin in both Dec and RA;
  - Tiles are aligned within 163 iso-declination bands.
  - Number of tiles on the sky = 34162
  - Required storage assuming 4 Bytes/pixel, 12 products/tile = 27.51 TB



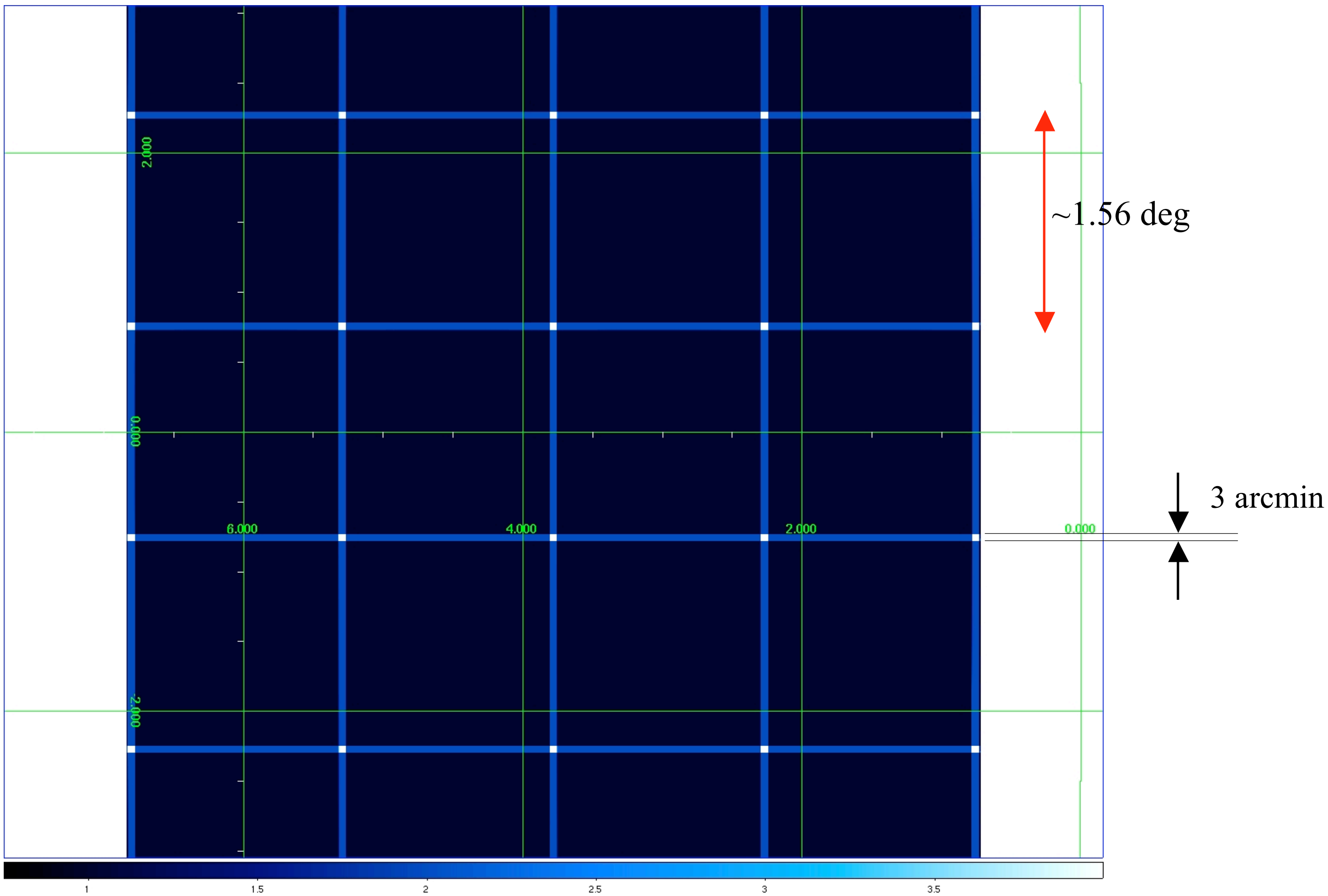
Tiling Geometry contd..

- **<u>Case 2:</u> 4096 × 4096 pixels at 1.375 arcsec/pixel (=1/2 native pixel size):**
  - Linear tile sizes: ~1.564 degrees;
  - Position angles of all image tiles are zero;
  - A *minimum* linear overlap between any two adjacent tiles of 3 arcmin in both Dec and RA;
  - Tiles are aligned within 119 iso-declination bands.
  - Number of tiles on the sky = 18241
  - Required storage assuming 4 Bytes/pixel, 12 products/tile = 14.69 TB



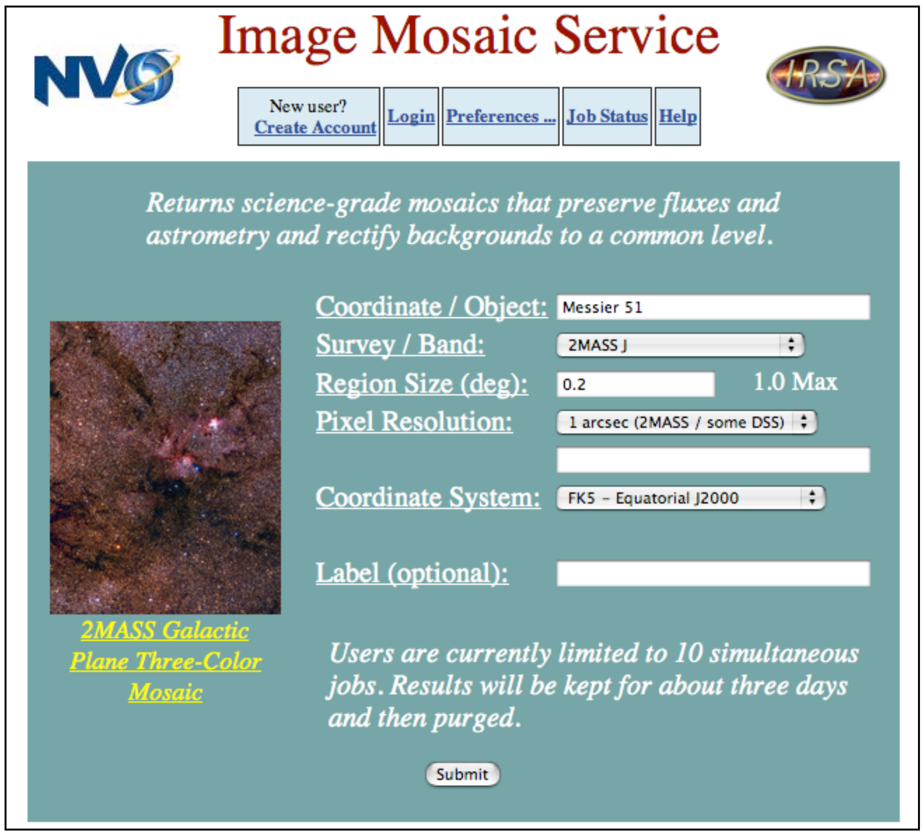
Tiling Geometry contd..

Case 2 again (4096 × 4096 pixels at 1.375 arcsec/pixel) on the Equator:



Co-add Pixel Query Service

- Atlas Image products will be accessed via a WISE image server interfacing with IRSA. Users can retrieve a co-add *portion* based on sky location, spatial extent, orientation and pixel scale.
- Maximum query size will be at least $1^\circ \times 1^\circ$ (constrained by server load and algorithm - TBD).
- Note: IRSA already provides a mosaicking and an image cutout service, e.g:



COADD Pipeline Overview

INPUTS:
- instrumentally and phot. calibrated, pointing refined science frames (level-1B): bands 1-3:1016^2; band 4: 508^2;
- bad-pixel masks (also records opt artifacts, latents);
- uncertainty (sigma) frames;
- list is queried from region centered on predefined sky tile.

- Gain/throughput matching (*multiplicative*) so to scale input frames to single photometric zero-point.
- Frame background matching (*additive*).

Outlier detection/flagging

Interpolate frames (using kernel optimized for outlier detection) onto common pixel grid.

Outlier detection on interp. pixel stacks using robust methods (e.g., median, MADs, quantiles) → *Frame masks updated.*

Check and rescale (if necessary) error model uncertainties against variance in repeated frame measurements (χ^2 stats).

Co-addition of all good (unmasked) detector pixels using **AWAIC:** *A WISE Astronomical Image Co-adder.* Uses a more optimal interpolation procedure with uncertainty weighting.

OUTPUTS:
- main intensity image (rate ∝ DN/t units), MAGZP in headers.
- coverage map/image
- uncertainty image
- 4096 x 4096; ≤1.375″/pix (TBD)
- QA metrics: backgrounds, noise, coverage distributions.

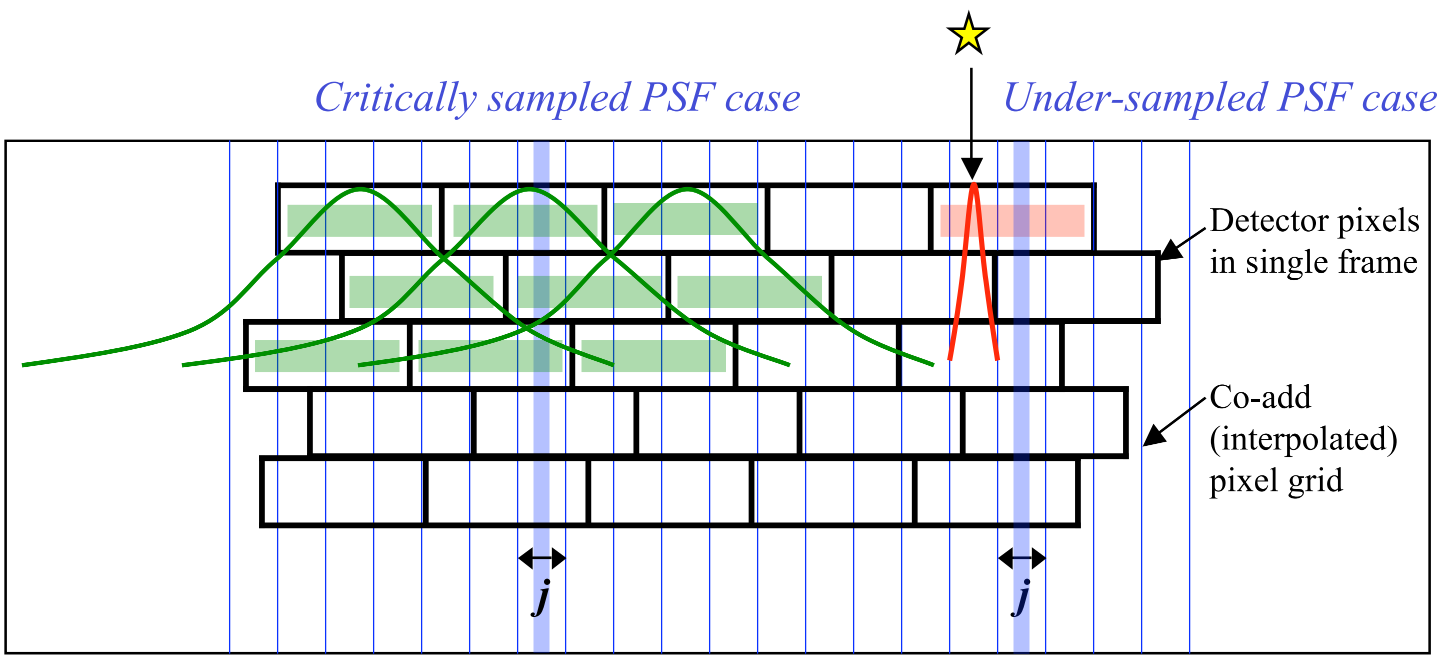
Atlas Image FPG; products registered in database and indexed. Will interface with IRSA's WISE image server.

Background Matching

- Goal: obtain seamless (or smooth) transitions between frames across overlaps in a co-add. We want to equalize background levels on frame-to-frame scales but preserve natural background variations if possible.
- Varying background levels mainly due to varying instrumental effects and transients.
- Within Atlas Image tiles (~1° – 1.5°), we can tie the levels of the frames to a single value - e.g., the median or a sigma-clipped average of all the input levels, or, to the median values in frame overlap regions (the 2MASS method).
- We want to first make each Atlas Image tile self-consistent for scientific purposes.
- Then need a general background matching method for internally stitching tiles together in the WISE image server. E.g., a user may query a region that straddles a tile boundary.
  - Only performed if background levels between adjacent tiles significantly differ (outside background uncertainties).
  - Nice methods have already been developed, e.g., *Montage*, *Spitzer* (MOPEX, MIPSGAL project)
  - These use "global minimization algorithms". To prevent solutions from veering off to large ridiculous values, we need a constraint, e.g., tie to absolute (DIRBE) background with a smoothly varying scale factor, or, large scale averages.
- Derive a single photometric zero-point for a co-add from input zero-point values. This may involve possible scaling of input frame levels if systematics severe. Done before *offset* matching above.

Outlier Detection

- Take advantage of the redundancy in multiple frame exposures and flag inconsistent measurements in the temporal domain.
- For a lack of better and faster methods from other projects/literature, we adopt the brute force approach where all frames are first projected and interpolated onto a common grid, then an outlier identification algorithm is applied to each pixel stack.
- It helps to have good sampling of the PSF for temporal outlier rejection! WISE will be better than critically sampled in all bands
- If under-sampled (even moderately so), there is the possibility of flagging real sources as outliers! Here the *red pixel* will be erroneously identified as an outlier with respect to samples stacked in co-add pixel *j*. => Reliability plummets. Solution: Make the outlier search window bigger and bump up the threshold. But will now miss the weak outliers.
- There are always trade-offs between completeness and reliability.



Outlier Detection method..

Main steps:

1. Project and interpolate frame pixels onto a common grid and store values from all pixel stacks. To circumvent memory overflow, we can partition the grid into sub-areas, then identify outliers in each separately.
2. For each pixel stack in interpolated space, compute *robust* moment measures of their flux distribution and save as image files on disk (for later QA), e.g., median and sigma measures from either quantiles or the MAD measure:

$$\sigma_j \approx 0.5(p_{84} - p_{16}) \quad \text{or} \quad \sigma_j \approx 1.483\, median\{|p_i - median\{p_i\}|\}$$

3. Test an interpolated pixel with value p_i in stack j for "outlier status" if it satisfies the following criteria:

$$p_i > median\{p_i\} + t_{thres}\sigma_j$$

or

$$p_i < median\{p_i\} - b_{thres}\sigma_j$$

4. Flag outliers in frame-processing (bad-pixel) masks to propagate downstream
5. When building the final co-add, read in the masks and omit outlier pixels entirely from the co-add.

- Above method provides an independent *robust* measure of sigma as represented by the redundant measurements across multiple frame exposures; ⇒ use to check (and re-scale) the computed sigmas that are initiated upstream using an error model.
- Moving objects (asteroids) will be flagged as outliers unless they're moving slowly (<~ PSF width between the nominal 94 minute orbits; ⇒ Co-adds will represent the "static" inertial sky.

Co-addition Goals

- To optimally combine all the available measurements into a *faithful* representation of the sky given all the instrumental effects, limitations, transients, cosmic rays etc.. have been accounted for.
- Another way of looking at this (which I prefer) is to ask: what model or representation of the sky propagates through the measurement process to yield the observations within measurement error?

- The measurement process is effectively a filtering operation performed by the instrument's Point Response Function (PRF):

$$Sky \rightarrow \underbrace{PSF \otimes \Pi}_{PRF} \times sampling\ by\ pixels \rightarrow measurements$$

- The PRF represents the real transfer function. Each pixel collects light (information) from its vicinity with an efficiency described by the PRF. The better the sampling, the larger its domain of awareness.

- The PRF represents the most *optimal* interpolation kernel for use in co-addition and 'reconstructing the sky' from the measurements. For detector measurements D_i, the flux in a co-add pixel *j* is given by:

$$f_j = \frac{\sum_i r_{ij} D_i}{\sum_i r_{ij}} \quad ; \quad r_{ij} = \text{response at location } j \text{ from a detector pixel at } i.$$

- In co-adders that use overlap-area weighted averaging (e.g., MOPEX, *Montage*, other..), the interpolation weights are the actual overlap areas $r_{ij} = a_{ij}$. In fact, for severely under-sampled PSFs, the above method reduces to area-weighted averaging. In this limit, the PRF becomes top-hat.

Co-addition in AWAIC

AWAIC - A WISE Astronomical Image Co-adder. **What makes it 'wise'?**

Advantages of AWAIC over other co-adders *for WISE* (e.g., MOPEX, 2MASS, *Montage*):

- PRF interpolation reduces the impact of bad/masked pixels if the data are well sampled (even close to critical). This leads to effectively non-zero coverage at bad pixel locations on sky due to the extended PRF tails.
- Uncertainty estimation from a propagated error model, χ^2 sanity checks, and correlated noise corrections.
- The output signal and noise co-adds can be combined to define the *most optimal* matched filter for point source detection.
  - High frequency noise is smoothed out without affecting the point source signal sought for => SNR of peaks is maximized.
  - This will benefit processing at the WSDC since a source catalog is one of its release products.
  - See Ken Marsh's presentation on MDET (point source detection).
- Allows for any interpolation kernel to be specified, i.e., matched to the observations.
- Is capable of resolution enhancement (HIRES) through a Richardson-Lucy like procedure. Note: this is not in the WISE baseline plan. Used for offline research later.

Disadvantages:

- An extended interpolation kernel will "smear" sharp-edged features such as CR spikes on the co-add grid. These can masquerade as real sources if not properly flagged beforehand. Smearing is minimized in area-weighted (or top-hat PRF) interpolation methods where spike artifacts remain more pronounced.
- Noise is correlated on larger spatial scales in the co-add. Must be accounted for when performing photometry off the co-add - either aperture or profile fitting. Correlations are minimized for compact (top-hat) PRFs.

AWAIC Processing Flow

INPUTS:
- instrumentally and photometrically calibrated, background matched science frames with best (refined) WCS and distortion in FITS headers; queried from DB within predefined region.
- accompanying “bad” pixel masks (with suspect outliers flagged)
- accompanying uncertainty (sigma) frames;
- list of FPA position-dependent PRFs.
- Processing params: pixel size ratios, desired WCS of co-add

Initializations, check inputs for consistency, assign defaults.

Set-up output WCS of co-add (internal) **cell grid** onto which an up-sampled PRF with same pixel scale is mapped. Location and dimension of co-add grid (tile) predefined.

AWAIC BRAIN: Main processing loop (see more detailed flowchart): project pixels with distortion correction; map and interpolate detector PRF values onto internal cell grid; build up “mean” co-add using PRF-weighted averaging; optionally iterate if HIRES desired.

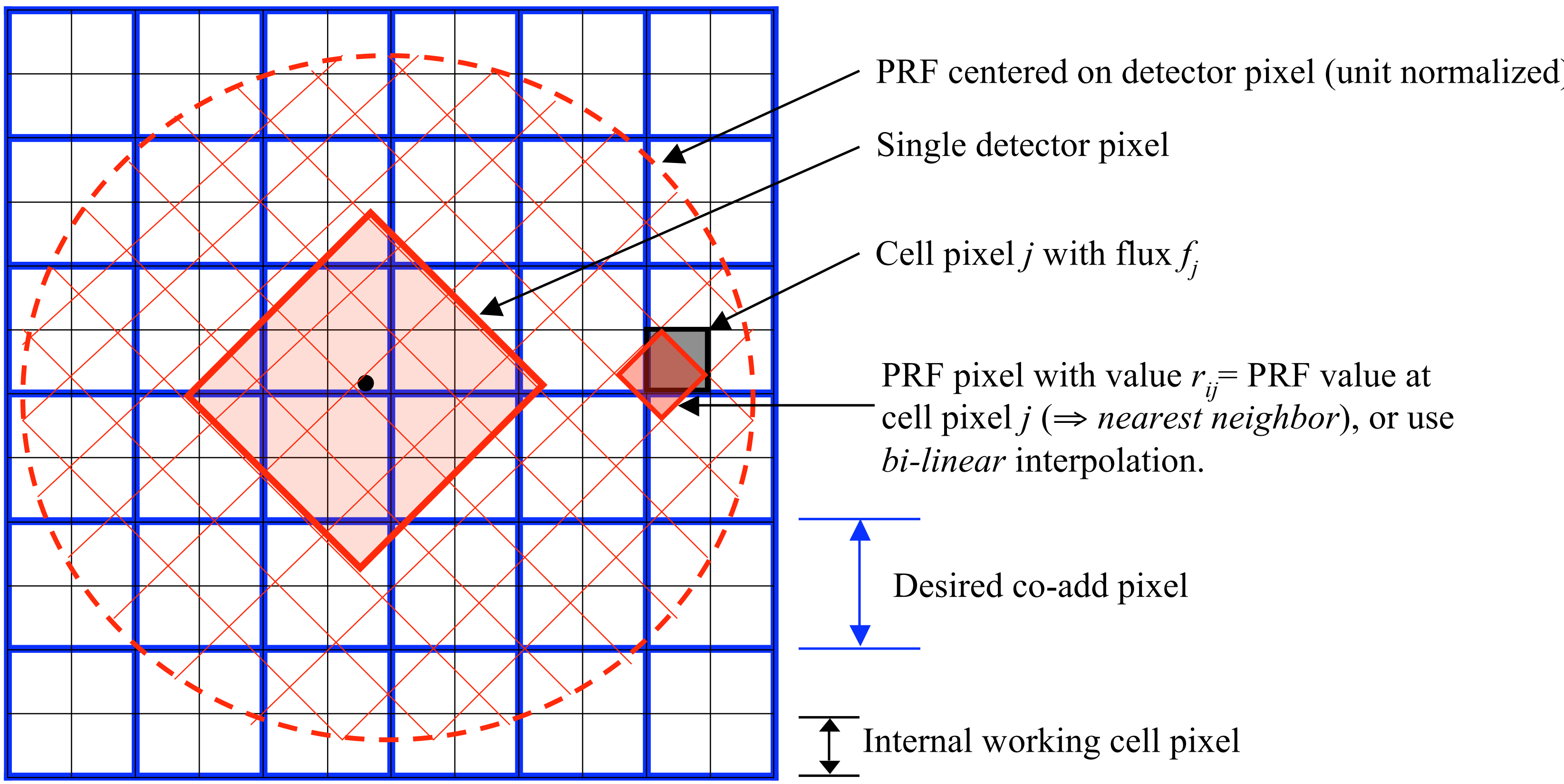
Down-sample and trim all internal cell grid products to desired final co-add pixel scale and dimensions.

OUTPUTS:
- Main intensity image;
- Uncertainty image;
- Depth-of-coverage map;
- Log of I/O, processing status and runtime;
- QA diagnostics;

NOTES
- Projection and distortion correction uses “fast algorithm” developed at *Spitzer* and also used in *Montage*.
- *flux* = PRF / inverse-variance weighted average:

$$\langle f_j \rangle = \frac{\sum_i \frac{r_{ij}}{\sigma_i^2} D_i}{\sum_i \frac{r_{ij}}{\sigma_i^2}}$$

PRF Placement and Interpolation



- PRF is sampled on same scale as an internal cell pixel (offline calibration once cell size optimized).
- Flux from cell pixel contributing to measured flux in detector pixel $i = r_{ij} * f_i$
- At end, co-add values in cell grid are down-sampled to desired final co-add pixel scale.

Example: NGC 2403
Spitzer-IRAC (3.6μm)

~ 13′

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North Ecliptic Pole
Spitzer-IRAC (3.6μm)

Frame Co-addition

~ 35′

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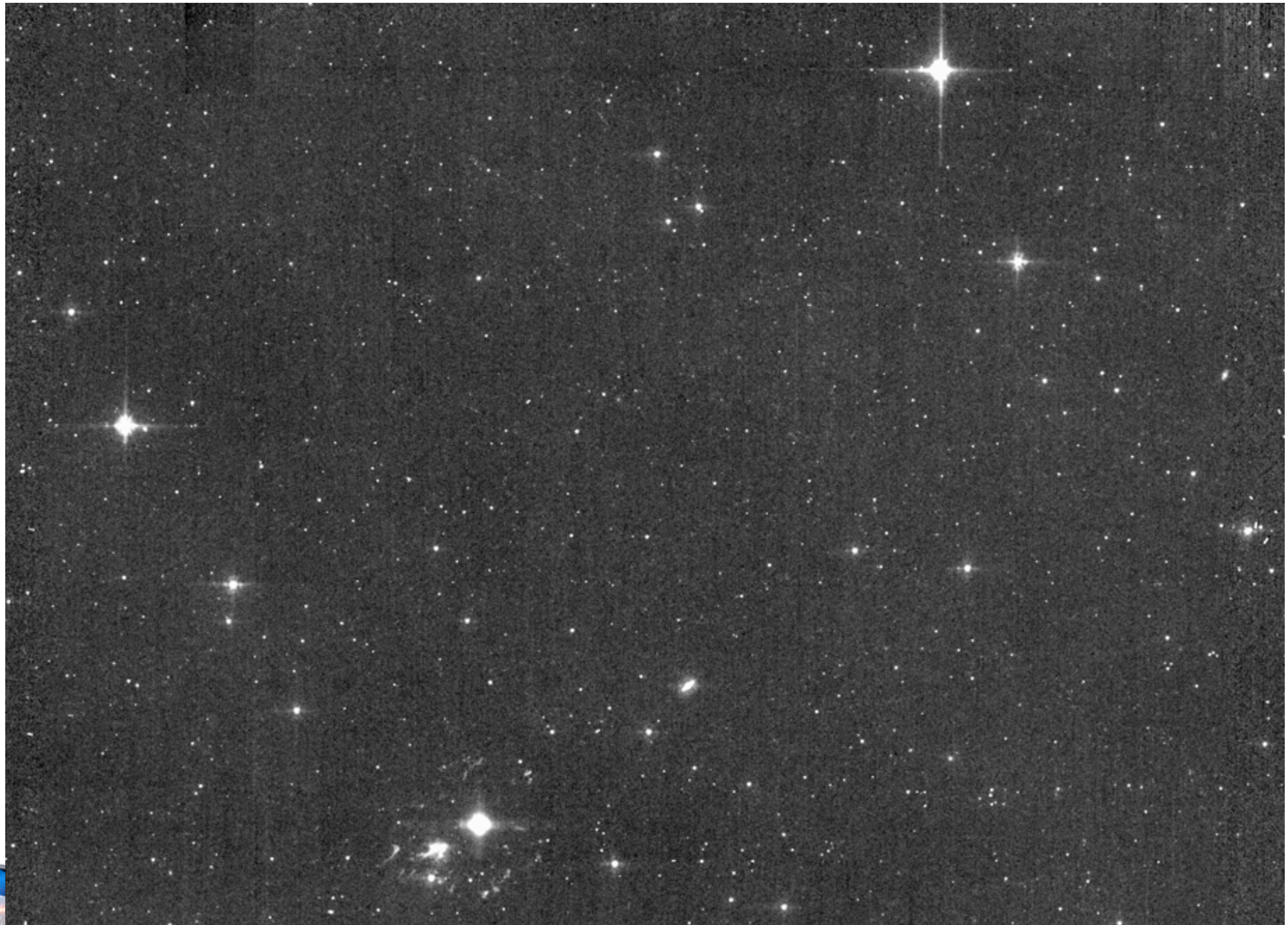
North Ecliptic Pole
Spitzer-IRAC (5.8μm)

Frame Co-addition

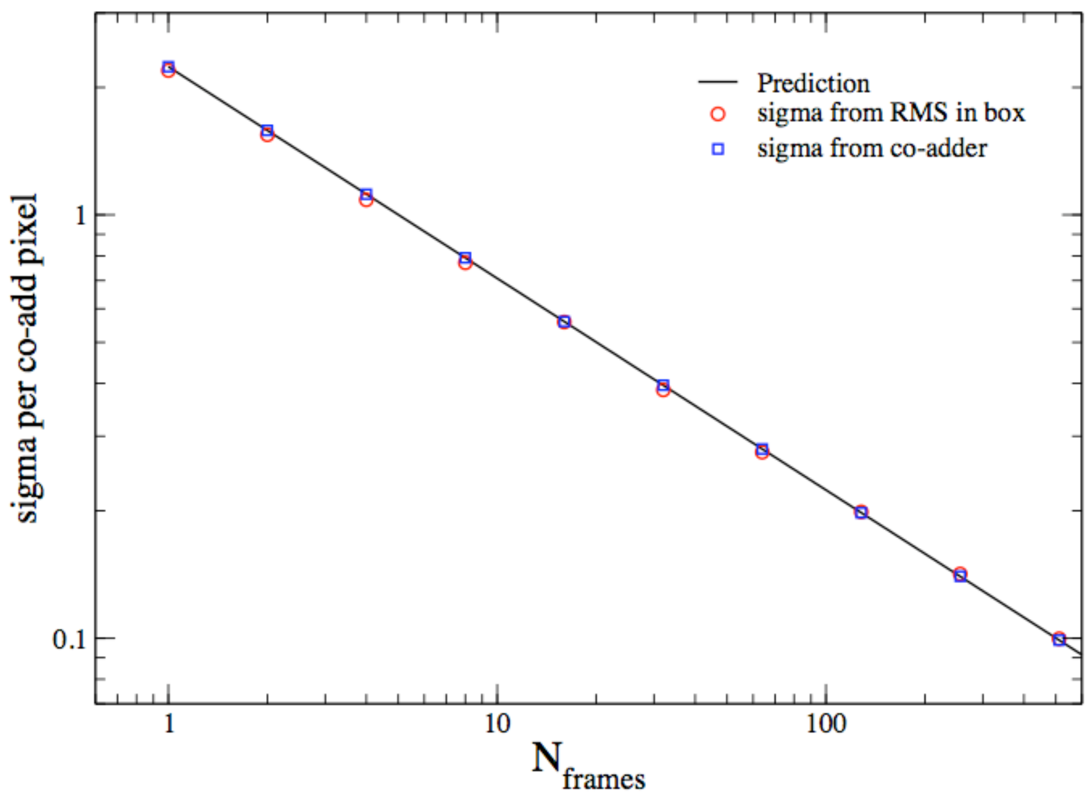


~ 35′

Noise Characterization

Co-add pixel noise scales as expected with the input number of frame overlaps (depth-of-coverage):

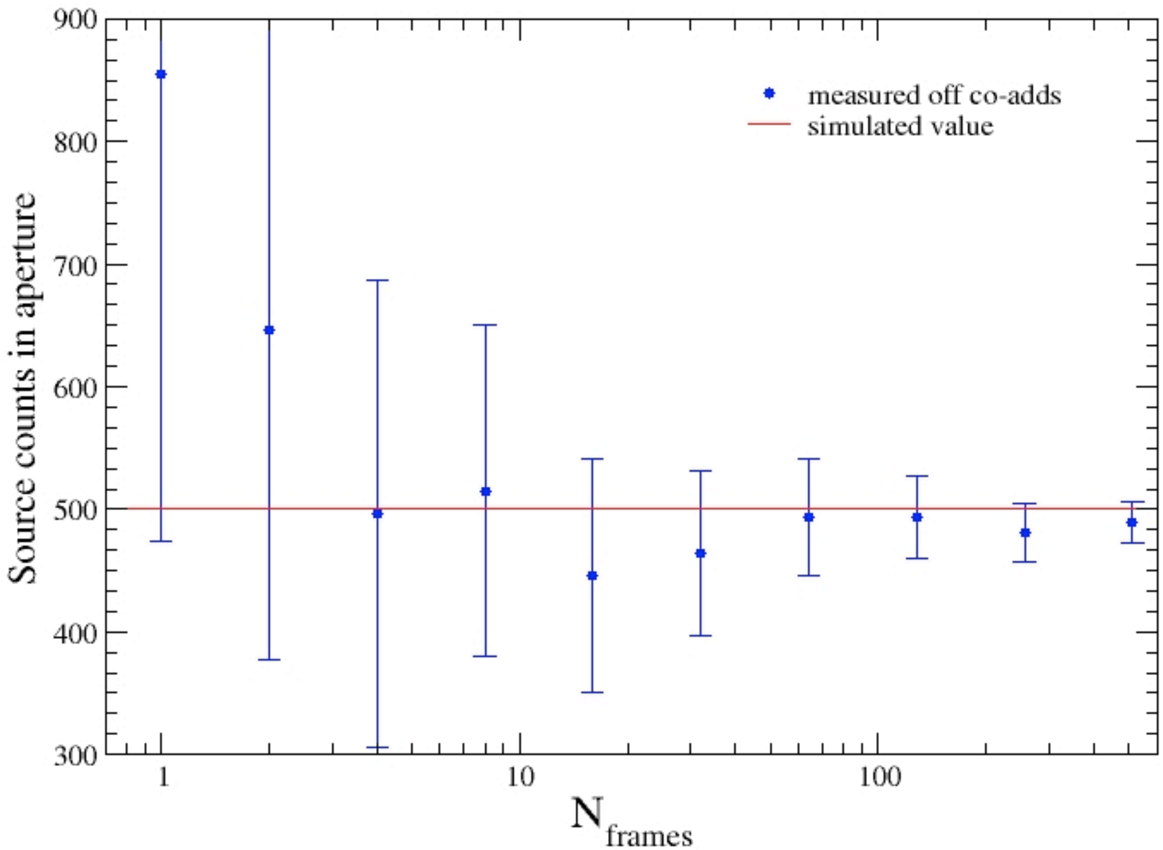
$$\sigma_p \propto \frac{1}{\sqrt{N_{frames}}}$$



Noise in Aperture Photometry

Uncertainty in total flux measured in an aperture (or profile fit) off co-add will be affected by correlated noise.

- Formalism is outlined in Subsystem Design Specification document.
- Ignoring correlations would lead us to over-estimate Signal-to-Noise ratios => over-confident about our measurements!
- We plan on providing a look-up table or graph of correction factors as a function of aperture size to correct for correlations.



Summary from Peer Review

- Peer review on frame co-addition was held November 15, 2007 at IPAC.

- Main discussions, recommendations and suggestions:

  - Rules of thumb provided on optimum pixel sizes and number of frames for outlier detection from people's *Spitzer* experiences.
  - Existence of drastic trade offs between completeness and reliability when detecting outliers in low-to-moderate coverage cases.
  - Potential biases when weighting inputs using Poisson derived variances.
  - Use WISE cyclotron test data as input for testing outlier detection algorithms.
  - Artifacts from the Rice-(de)compression can be flagged using temporal outlier detection methods.
  - Pitfalls of global minimization methods for background matching when there are no absolute constraints.
  - Spatially varying flat-fielding residuals in input frames may wreck havoc since they cannot be corrected by most simple background matching algorithms.
  - Physical meaning of *fractional* versus *integral* coverage values can lead to confusion.
  - Possible large Inter-pixel Capacitance (IPC) effects may exist in the background limited bands (3 and 4). This will broaden PRFs and exacerbate correlated noise in co-adds.
  - A mosaic of the standard deviations across repeated observations has proved to be very useful on *Spitzer*.
  - Not to spend too many resources on HIRES'ing if not in baseline plan.

Development Schedule

- **Version 0 - 8/30/2007:** *prototype and dataflow infrastructure*
  - Basic co-addition with bad pixel masking complete
- **Version 1 - 5/31/2008:** *input test / simulation data with signatures from ground characterization*
  - Selection of specific mask bits to flag against using specifiable bit-string template
  - Outlier detection and rejection implemented. Completeness/Reliability analysis
  - Uncertainty model versus repeatability checks and input uncertainty rescaling
  - Frame background (gain/throughput and offset) matching implemented, rescaling of calibration zero points in co-add headers
  - Sky tiling geometry for Image Atlas settled: dimensions and pixel sizes
  - IRSA-WISE image server capabilities, infrastructure and budgeting
- **Version 2 - 11/30/2008:** *mission scenario testing using simulations and Spitzer data*
  - Frame co-addition pipeline thread/wrapper
  - QA diagnostics and metrics on Atlas Image tiles defined and implemented; trackback utility
  - Sky tiling and frame indexation/querying scheme in place with DB infrastructure
  - Atlas Image stitching/background matching algorithms (for IRSA image server) designed
  - Atlas Image FITS and DB metadata defined

Development Schedule

- **Version 3 - 6/30/2009:** *operations readiness testing, launch, IOC*
  - Optimization: analytic fits to input PRFs; FFTs to speed up convolution steps (TBD)
  - Noise-correlation correction factors to assist aperture photometery off co-adds (for explanatory supplement)
  - Final Product Generator (metadata integrated with image server)

- **Version 3.5 - 12/30/2009:** *tune-up pipelines/modules according to on-orbit performance*
  - Input parameter tuning: outlier thresholds, interpolation accuracy, masking bit templates
  - Point Response Functions (versus array location, brightness[IPC?] if necessary) derived
  - Further optimization (if needed)
  - Quality assurance (with feedback to other subsystems): e.g., temporal variations from frame stacks at poles to tune upstream instrumental calibrations, distortion, pointing accuracy.
  - Start to distill documentation/analysis pages into Explanatory Supplement

- **Version 4 - 9/20/2010:** *reprocessing (final processing pass)*
  - Tune up: derive best or scan-matched PRFs, thresholds, optimized to support final reprocessing
  - HIRES improvements for offline use/research.

Further reading

- Summary of WISE co-adder with examples:
  http://web.ipac.caltech.edu/staff/fmasci/home/wise/awaic.html

- Subsystem Design Specification (SDS):
  http://web.ipac.caltech.edu/staff/fmasci/home/wise/sds-wsdc-D005-v2.8-awaic.pdf

- Atlas Image tiling geometry examples:
  http://web.ipac.caltech.edu/staff/fmasci/home/wise/tiling.html

- Atlas image specifications and plans:
  http://web.ipac.caltech.edu/staff/fmasci/home/wise/Atlas_image_spec_v1.2.pdf