WISE Atlas Image Specification

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1. Introduction

One of the products from the WISE mission is an Image Atlas. This will consist of single-band images created from a co-addition of multiple frame exposures within pre-defined regions on the sky. This document presents a *proposal* for their sizes, formats, informational content, projection properties and tile geometry. Comments and suggestions on all aspects are welcome.

1.1. Requirements

Below we summarize the (level-4) requirements pertaining to WISE Atlas Image products. These are from the *WSDC Functional Requirements Document*:
http://web.ipac.caltech.edu/staff/roc/wise/docs/WSDC_Functional_Requirements_all.pdf

- **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-021:** The images in the final WISE Image Atlas shall be re-sampled to a common pixel grid at all wavelengths.
- **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-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-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-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.

- **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 select on any image metadata parameter.
- **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.

2. Atlas Image Products

- We are planning on delivering three image products per footprint (tile) on the sky: the primary Atlas intensity image, and two accompanying ancillary images: a depth-of-coverage map and an uncertainty image.
- The intensity image represents a co-add of all multiple frame exposures that fall within a footprint. This will be computed using a weighted mean of the input frame pixels, appropriately interpolated onto an up-sampled co-add grid.
- The coverage map will be of the same size as the Atlas Image and will effectively indicate how many times a point on the sky was visited by a "good" detector (FPA) pixel, i.e., not rejected due to prior-masking, cosmic rays or other transients.
- The uncertainty image will contain a 1-sigma error estimate in the co-added signal for every Atlas image pixel. These uncertainties will implicitly contain the result of the full error-propagation from the instrumental calibration pipeline. These are initiated using an error-model and then appropriately re-scaled according to the degree of repeatability over multiple frame exposures.
- These products will be generated in a WSDS software subsystem currently under development. Very briefly, this software will re-project, undistort and interpolate frame pixels onto a co-add grid, omit 'bad' pixels flagged upstream, perform outlier detection and rejection from statistics of stacked frames, and equalize frame backgrounds.
- With three image products per band, this means 12 products per footprint on the sky.

3. Footprint Definition, Size and Delivery Formats

- This proposal calls for an Atlas Image to consist of 2048 × 2048 pixels with a projected pixel scale at the center of 1.375 arcsec (= half the native pixel size of a WISE FPA);
- This corresponds to a linear dimension of ~ 46.93 arcmin when an image is projected onto the sky, i.e., about the same size as the WISE FOV (that includes the 'inactive' reference pixels);
- The prime motivation for these sizes is twofold: (i) enable efficient transfer of products over the web (storage sizes are below); and (ii) enable one to display an entire Atlas Image with sufficient detail and a minimum of fuss on their monitor. Of course, this depends on the size of a monitor, and we're guessing 12 - 24 inch monitors are the norm. Zoom-in/out functionality is available on most image viewers and so some users may not find it annoying at all.
- We selected 2048 for the linear dimension (and not 2000 for example) so it can be represented as 2^n where n = positive integer. This will be useful for algorithms that require sizes expressible as a power of two (e.g., FFTs).

- The choice of pixel size is motivated by the on-orbit (pseudo-) random dither/stepping pattern, and the eventual storage size (total number of pixels). To get all the gain when combining interleaved frames, i.e., for optimal sampling of the underlying PSF and source centroiding, we need a co-add pixel size of <~ $2.75N^{1/2}$ arcsec, where 2.75 arcsec is the native detector pixel size in bands 1, 2, and 3 (5.5 arcsec in band 4), and N is the coverage-depth. Given N~8 at the ecliptic equator and N~1000 at a pole, this suggests co-add pixel sizes of <~1 and <~0.1 arcsec at the equator and a pole respectively for bands 1 – 3. Band 4 limits are a factor of two larger. As a compromise between keeping images to a manageable size, and still ensuring good on-average sampling/positioning of point sources on a co-add, we selected half a detector pixel size (1.375 arcsec) as the Atlas Image pixel size across all bands.
- Each image pixel shall be represented as a 4-byte floating-point number. With 12 images per footprint across all bands, this means a total of $12 * 2048^2 * 4 \cong 201.33$ MB per Atlas Image product.
- One way to package the Atlas Image data is using FITS cubes. Not all users will be interested in downloading all bands, and so an option is to package the products *for each band* into separate cubes, i.e., three planes per cube: intensity, uncertainty and coverage image. Users then have the flexibility to download any band-specific "Atlas Image cube".
- The size of an Atlas Image cube will be ~50.33 MB *per band*. This size will not be too cumbersome to download from a remote site (e.g., home). Users with access to a standard DSL modem (with connection speed ~270kB/sec) will be able to download such a cube in ~3 minutes.
- You may be thinking: why not package all the Atlas (intensity) images for all four bands in a four-plane cube, the coverage maps in a separate cube, and uncertainty images in another cube so that we have three four-plane cubes each ~67.1 MB in size. The problem here is that users may not download the coverage and uncertainty cubes if they have to be downloaded separately. These are necessary if one wants the full scientific benefits of the Atlas Images.
- Another option is to leave the three products per band as single-plane FITS files and then *zip* or *tar* these for each separate band into files prior to distribution. A lossless compression method (e.g., *gzip* or *compress*) will also be employed. This would reduce file sizes by about 25 to 35%.
- So the options are: have an 'Atlas Image cube' for each band, each consisting of three planes corresponding to: an intensity, uncertainty and coverage-depth, or, a single zipped (or tarred) file for each band containing these products as single-plane FITS files. These options are up for discussion.

4. Metadata and Image Units

Since Atlas Image products will be packaged into FITS files, we need to define some metadata and information for the FITS header. A sample FITS header, assuming one "Atlas Image cube" per WISE band is below. Note that if we decide on FITS cubes as the distribution format, a FITS header will be generic to all planes of a cube.

```
SIMPLE  =                    T / file does conform to FITS standard
BITPIX  =                  -32 / number of bits per data pixel
NAXIS   =                    3 / number of data axes
NAXIS1  =                 2048 / length of data axis 1
NAXIS2  =                 2048 / length of data axis 2
NAXIS3  =                    3 / length of data axis 3
CRVAL1  =           114.125000 / RA at CRPIX1,CRPIX2, J2000.0 (deg)
CRVAL2  =            65.600000 / Dec at CRPIX1,CRPIX2, J2000.0 (deg)
EQUINOX =               2000.0 / Equinox of WCS, (year)
CTYPE1  =           'RA---SIN' / Projection type for axis 1
```

```
CTYPE2  =           'DEC--SIN' / Projection type for axis 2
CRPIX1  =               1024.5 / Axis 1 reference pixel at CRVAL1,CRVAL2
CRPIX2  =               1024.5 / Axis 2 reference pixel at CRVAL1,CRVAL2
CDELT1  =      -0.000381944444 / Axis 1 scale at CRPIX1,CRPIX2 (deg/pix)
CDELT2  =       0.000381944444 / Axis 2 scale at CRPIX1,CRPIX2 (deg/pix)
CROTA2  =            74.500000 / Image twist: +axis2 W of N, J2000.0 (deg)
ELONG   =           119.453441 / Ecliptic longitude at image center (deg)
ELAT    =             5.230984 / Ecliptic latitude at image center (deg)
GLONG   =            31.157443 / Galactic longitude at image center (deg)
GLAT    =            15.910982 / Galactic latitude at image center (deg)
TELESCOP=               'WISE' / Telescope used to acquire data
BAND    =                    3 / Wavelength band number
BUNIT   =                 'DN' / Image pixel units (applicable to planes 1&2)
MAGZP   =              21.8403 / Calibrated photometric zero point (mag)
MAGZPUNC=                 0.02 / Uncertainty in calibrated zero point (mag)
ATLASID =                  124 / Atlas image tile ID
ORBSEQ  =         '5065..5102' / Range of orbit (scan) IDs used
NUMFRMS =                   73 / Number of frames used (falling in footprint)
COMMENT  This is a three plane cube:
COMMENT     Plane 1: Intensity image (units: DN)
COMMENT     Plane 2: Uncertainty image (units: DN)
COMMENT     Plane 3: Depth-of-coverage image (= effective # input pixels)
HISTORY  aWaic: A WISE Astronomical Image Coadder; Vsn 1.1
HISTORY  Version of processing pipeline: v. 1.321
DATE    = '2007-10-09T17:18:05' / file creation date (YYYY-MM-DDThh:mm:ss UT)
END
```

Notes:

- Pixel values in all planes will be in IEEE single precision floating point (BITPIX value).
- The BUNIT keyword value is only applicable to planes 1 and 2. The reason for having pixel values in native Data Number (*DN*) units is that this convention is independent of any assumed calibration conversion factor. It will be computationally expensive to update all Atlas Image pixels (and source extraction records) for changes in conversion factors from the photometric calibration. Instead, we shall store any calibration conversion factor or offset as a single header keyword, e.g., MAGZP. This will be applicable to all pixels of an Atlas Image. This follows the 2MASS convention.
- Initially, WISE photometry will be relative to its own photometric standards. A calibration zero-point in magnitudes (MAGZP) will be derived there from. To convert from *DN* (or integrated, sky-subtracted *DN* in an aperture), a user would then compute the calibrated magnitude using: $\mathrm{MAG} = \mathrm{MAGZP} - 2.5 * log_{10}[\ DN\ ]$. Note that the *DN* here is effectively a rate (slope), not a raw detector count. Therefore, these are already scaled in terms of total exposure time (depth-of-coverage).
- We may also want to add some important QA metrics to the header, e.g., pixel value percentiles, global gradient measures, etc.. It's all up for discussion.

5. World Coordinate System and Projection

- You may have noticed in the sample FITS header above that the World Coordinate System (WCS) is represented as equatorial. In fact, this is our plan. There are three motivations:
    i. to enable efficient cross-referencing/association with existing astronomical source catalogs and on-line image databases where positions are most likely to be in the conventional equatorial system;

  ii. make use of “fast” plane-to-plane re-projection algorithms (in the presence of optical distortion) recently developed for this WCS. These are used in *Spitzer* and *IRSA* processing. Due to their complication, equally fast re-projection algorithms are yet to be developed for the ecliptic and galactic WCS. Re-projection and un-distortion of detector images onto a common co-add grid is usually the most computationally intensive step of a co-addition process;
  iii. when represented by keywords that conform to the FITS standard (e.g., sample header above), most astronomical image viewers can readily deal with the equatorial system and the associated projection types. This is because most viewers use a standard set of WCS library routines (e.g., WCSLIB, WCSTools). These libraries have been endorsed by the IAU FITS Working Group.

- Numerous projections that map a sphere (or portion thereof) onto a flat plane have been invented. The most often used projections in astronomy are the TAN (gnomonic) and SIN (orthographic) projections. These are illustrated in the 1-D schematic of Figure 1. The ‘run’ of linear scale (D) on the plane with angular distance θ on the sky defines the projection properties. The **SIN** projection is ‘natural’ in the sense that it represents the projection of a sphere when seen from a great distance. For this projection, the angular size of a pixel on the sky scales as $d\theta/dD \sim$ CDELT/cos(θ) where CDELT is the pixel scale at the tangent point (image center). This means pixel scale increases with increasing distance (θ) from the image center and you can fit “more sky” onto your SIN-projected plane (co-add). Depending on the angular distance, objects can also appear squashed at the extremities! The opposite is true for the **TAN** projection. Here, the angular size of a pixel scales as $d\theta/dD \sim$ CDELT*$\cos^2(\theta)$. Thus the pixel scale becomes smaller with increasing distance from the image center, you get “less sky” per pixel and objects get stretched. In general, the pixel scale varies more strongly with θ for TAN (i.e., is more non-linear) than it does for SIN.
- For the proposed Atlas Image sizes: ~23.5 arcmin from their tangent points, it turns out that the difference between SIN and TAN is minuscule. The pixel scales at the edges of our Atlas Images relative to their centers will differ by ~0.002% and ~0.005% for these projections respectively. For larger co-adds however, e.g., >~ 5 degrees in extent, distortions from projection will start to become important. Here, the relative pixel scales will differ by >~0.1% and >~0.2% for SIN and TAN respectively. We will not be generating and delivering image products of this size, but the external community may want to create them manually by registering and re-projecting the nominal Atlas Images. For this purpose and the reasons just outlined, we recommend that the SIN projection be used.
- Thus, given the slight advantages in using the SIN (orthographic) projection, in particular for large image extents, we propose that we use it when generating the Atlas Images. In the end, it makes little difference for the scales we’re working at.

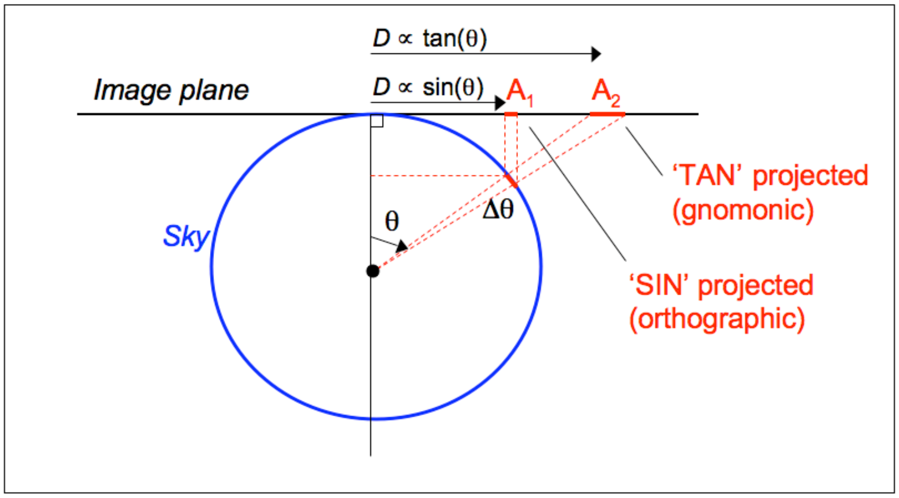

Figure 1: Exaggerated 1-D schematic of a portion of sky projected onto a flat plane. The same area on the sky (Δθ) is projected onto different scales in the image plane: A_1 and A_2 for SIN and TAN projections respectively.

6. Tiling Geometry on the Sky

- We want to be able to tile the Atlas Image footprints over the sky in some optimal manner. Some considerations/desirables are:
    i. cover the sky as uniformly as possible, i.e., have all image centers (tangent points) close to equidistant from each other;
    ii. any two tangent points should have a separation that will allow sufficient overlap between adjacent Atlas Images. This is driven by the typical size of objects/structures (e.g., galaxies) that one would want to retain in an image but which would otherwise fall on the edge of another. But note, more overlap implies more Atlas Images and hence storage space.
- The first point above is solved (for example) if we adopt the highly versatile HEALPix scheme. **Note:** this is only used for defining the distribution of footprint centers over the sky, *not the WCS-projection format*. HEALPix involves a hierarchical tessellation of the sky into curvilinear quadrilaterals (see Figure 2). What's important here is that the centers of HEALPix tiles on the sky are equidistant from each other in *iso-latitude* bands, and also moderately so between adjacent latitude bands. There are other advantages too: (i) it provides an indexing scheme on the sky to enable 'fast' searches and is becoming popular for large databases. (ii) to support later scientific applications: e.g., clustering and background intensity correlation analyses and comparisons to studies at other wavelengths and resolutions that use the same scheme.
- With an Atlas Image tangent point placed at the center of a HEALPix tile, the question now is: what should be the separation of the HEALPix centers such that there'll be sufficient overlap between the Atlas images?
- First, how much overlap do we want? 2MASS required 1 arcmin. We can be a little more conservative and adopt say a *minimum* linear overlap of 4 arcmin between any two adjacent images over the whole sky. We need to set a minimum because various geometrical effects (including assumed orientations) will tend to decrease and increase linear overlaps between the square images. Note: there is no convergence off the equator in the HEALPix construction.

- Without doing the full simulation, we can guesstimate the number of HEALPix tiles and hence the number of Atlas Images for the whole mission. We assume that the whole sky will be observed. Given the area of a HEALPix tile, $\Omega_{\rm pix}$, its characteristic 'side length' in the HEALPix hierarchy is $N_{side} \approx \mathrm{ceil}[(\pi/3\Omega_{\rm pix})^{1/2}]$, where the 'ceil' operator rounds up to the closest integer (i.e., for conservatism). The number of HEALPix tiles is given by $N_{pix} = 12N^2_{side}$. Given a linear overlap of 4 arcmin, this means we need a HEALPix tile area of order $(47' - 2*4')^2 = 1521$ arcmin^2. Doing the math, we need about 99372 HEALPix tiles or points over the sky at which to place our Atlas Image footprints. With 201.33 MB per four-band Atlas product, this amounts to ~20 TB for the whole Image Atlas. Lossless compression may get this down to 14 – 16 TB.
- If we go with the HEALPix tessellation scheme, a number of questions remain:
    1. Since the HEALPix tile centers follow an "iso-latitude" distribution of points (i.e., forming concentric rings of constant latitude), should these rings be aligned with lines of constant equatorial declination, ecliptic latitude, or neither?
    2. What about the orientation of the individual Atlas Images? A nice choice would be to make their Position Angle (PA) vectors (or physical Y-axes) perpendicular to the HEALPix iso-latitude rings. This is motivation for aligning the HEALPix iso-latitude rings with equatorial declination so that all PAs can simply be set to zero.

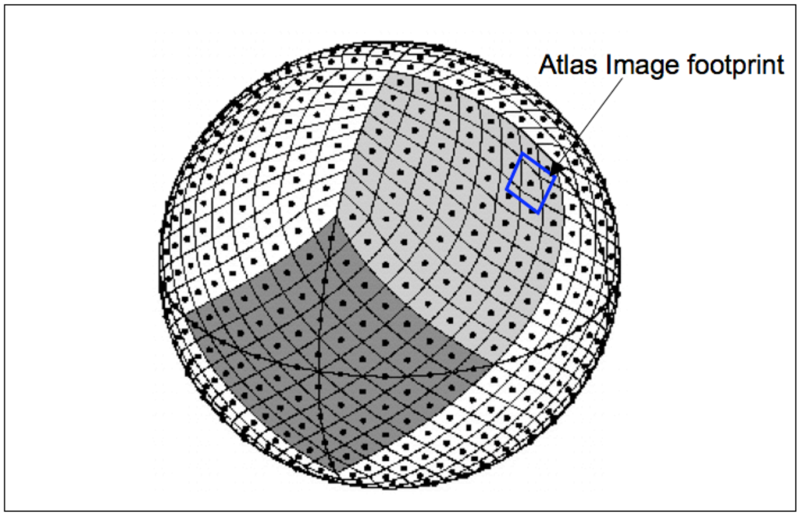

Figure 2: Orthographic view of a HEALPix partition of a sphere containing 768 tiles. This is purely for illustrating the distribution of equidistant tile centers – effectively the Atlas Image tangent points. The HEALPix tile sizes we predict for WISE (see text) would not be resolvable in this figure. Adapted from *Górski et al. ApJ, 622, 759*.

7. Frequency of Co-add Generation?

- There will be two full passes in processing of WISE data:
    1. The first pass will process image frames on-the-fly during on-orbit operations. A preliminary digital Image Atlas using data from the first 50% of the sky surveyed (requirement L4WSDC-005) will be generated in this pass.
    2. The second (post-flight) pass will make use of calibrations and configuration parameters optimized in the first pass to generate the final archival Image Atlas.
- During the *first pass* however, we will also want to dynamically generate co-adds for monitoring and quality assurance purposes.

- As a reminder, we will get full depth-of-coverage on the ecliptic equator after 15 orbits, giving a modal coverage of ~8 frames. As the mission proceeds, frame convergence towards the poles (CVZs) will cause the depth-of-coverage there to gradually increase. In fact, assuming that frames from each orbit will be approximately co-aligned at the poles, the pole coverage-depth is expected to increase at a rate ~15 frames per day (ignoring dropouts).
- It will be computationally expensive to re-generate co-adds for QA in a cumulative manner around the poles – i.e., combining all frames from the start of survey operations each time. Instead, we propose that these be generated incrementally as the survey proceeds from only the newest frames acquired over 1 day. This is because full coverage is attained on the ecliptic after ~1 day (15 orbits). Note: Atlas Images for the preliminary and final releases will be constructed using all available data falling within the predefined image footprints.

8. Summary of Issues and TBDs

1. Do we flag/mask pixels in an Atlas Image co-add that have low depth-of-coverage? In principle, the effective coverage as represented by a detector PRF on the sky can fall between 0 and 1. This will be indicated in the coverage map that's delivered together with the intensity image, but, do we want to explicitly indicate pixels with low coverage in the intensity image? These can be set as NaNs – effectively leaving "holes" in an image.
2. Do we package and distribute Atlas Image products as 'Atlas Image cubes' *per band*, each consisting of three planes corresponding to: an intensity, uncertainty and coverage-depth, or, a single zipped (or tarred) file for each band containing these products as single-plane FITS files? These products will be further compressed, e.g., using *gzip*.
3. What other metadata should be included in the Atlas Image headers? E.g., QA diagnostics?
4. Atlas Image projection type: does anyone object to the SIN (orthographic) projection? As described above, this has slight advantages over TAN. For your information, 2MASS adopted SIN for its Image Atlas.
5. Is the HEALPix tessellation scheme appropriate for defining the Atlas Image tangent points?
6. If so, how shall we orientate the HEALPix iso-latitude rings? The simplest is to align them with lines of constant declination. If so, a natural choice for the position angles (Y-axis orientations) of all Atlas Image footprints is zero.
7. Is 1 day appropriate for the dynamic and incremental generation of co-add products (for monitoring and QA)?