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WISE (Wide Field Infrared Survey Explorer)

Calibration Plan

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Wide-field Infrared Survey Explorer (WISE) Calibration Plan

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1 Introduction

1.1 Scope

The WISE Characterization and Calibration Plan describes the process by which instrumental measurements will be converted into WISE's end item data products in scientific units, the WISE Source Catalog and Image Atlas, which have attributes specified in the Project Level 1 and 1.5 requirements. This document contains descriptions of the tests, analyses and procedures that must be performed in order to deliver these data products. The calibration process is described for prelaunch, In-Orbit Checkout (IOC), survey, and post-flight phases. This plan also contains the receivables required by the project to complete the calibration and deliver the scientific data products. Finally, this document contains the description of error budgets for WISE performance metrics. The error budgets are derived based on the current best-available numbers and will be updated as ground test and on-orbit data become available.

This document provides the process by which the WISE team (including MOS, Science Team, contractors, Project Office, and WSDC) will provide the final calibrated WISE data products as specified in Levels 1 and 1.5.

1.2 Definitions and Acronyms

Requirement: A requirement specifies a condition, parameter, or capability with which the system design must be compliant, verifiable, and have a demonstrated achievement during the mission. All requirement statements will use the verb "shall".

Goal: A goal specifies a condition, parameter, or capability with which the system design will strive to be compliant. It is not mandatory that such compliance be verifiable or have a demonstrated achievement during the mission. All goal statements will use the phase "will as a goal".

Allocation: An allocation is a requirement which is derived by partitioning a higher level requirement into lower level component requirements and making an assignment of values to that lower level. All allocation statement will use the phrase "shall have an allocation of".

Verification Methods:

- ***Test:*** Test is a quantitative verification method to verify product conformance to specified functional characteristics or performance parameters.
- ***Demonstration:*** Demonstration is a qualitative verification method to show compliance to specified functional characteristics through exercising the product, generally without the need for precision test equipment.
- ***Analysis:*** Analysis is an engineering assessment or mathematical verification method that uses techniques and tools such as math models, prior test data, statistical data, simulations, or analytical assessments to confirm compliance with requirements with appropriate margins.
- ***Inspection:*** Inspection is a verification method in which examination or measurement of product physical characteristics, or the review of design, production, or test documentation, determines compliance with requirements such as workmanship, quality, physical condition and dimensional tolerance.

Flight-system: The WISE Flight-system includes all hardware and software that will be launched into orbit.

Facility: The WISE Facility is the WISE Flight-system plus the Ground Data Systems and Mission Operations facilities.

List of Acronyms	
2MASS	Two Micron All Sky Survey
ADCS	Attitude Determination and Control System
AR	Anti-Reflective
BATC	Ball Aerospace & Technologies Corporation
CSR	Concept Study Report
DN	Data Number
DRS	DRS, Inc. Subcontractor to SDL.
E/PO	Education & Public Outreach
FWHM	Full Width at Half Maximum
FITS	Flexible Image Transport System
FOV	Field of View
IPAC	Infrared Processing and Analysis Center (Caltech)
IOC	In-Orbit Check-Out
IRSA	NASA/IPAC InfraRed Science Archive
ITL	Incompressible Test List
JWST	James Webb Space Telescope
MIRA	Monterrey Institute for Research in Astronomy
MOS	Mission Operations
QE	Quantum Efficiency
PNe	Planetary Nebulae
PRF	Point Response Function
PSC	Point Source Catalog
PSF	Point Spread Function
RAID	Redundant Array of Independent Disk Drives
RSC	Rockwell Scientific Corporation
RSR	Relative Spectral Response

List of Acronyms	
SAA	South Atlantic Anomaly
SDL	Space Dynamics Laboratory
SNR	Signal to Noise Ratio
SUR	Sample Up the Ramp
TBD	To Be Determined
TBR	To Be Resolved
TDRSS	Tracking and Data Relay Satellite System
UCLA	University of California, Los Angeles
ULIRG	Ultra-Luminous Infrared Galaxy
USNO	U. S. Naval Observatory
WCS	World Coordinate System
WISE	Wide-field Infrared Survey Explorer
WST	WISE Science Team
WSDC	WISE Science Data Center (IPAC)

Table 1 List of Acronyms

1.3 Applicable Documents

MIDEX AO 01-oss-03 July 16, 2001
WISE CSR--Updated
WISE Level 1 Requirements (L1) (JPL/D34056)
WISE Level 1.5 Requirements (L1.5)
WISE Facility Requirements Document (JPL/D30564)
WISE Payload Requirements Document (SDL/03-373)
SDL Payload Electro-Optical Characterization Plan (SDL/05-091)
WISE In-Orbit Checkout Plan (JPL/D38048)
Spacecraft Requirements Document (JPL/30569)
WISE MOS Requirements Document (JPL/30571)
SDL Master Test Plan (SDL/05-121)
WISE Alignment Plan (JPL/34391)

1.4 Document Organization

This document is organized into 5 sections. The first section is this introduction. The second section presents the mission overview, and the third section describes the process by which the WISE instrumental data will be calibrated for the various mission phases. The fourth section presents the receivables that must be delivered by the project in order for the process given in Section 3 to be carried out. The fifth section presents the error budgets for the WISE end item data products.

2 Mission Characteristics

This section provides a brief description of the WISE mission and science characteristics. The broad set of mission phases and scenarios are defined.

2.1 Science Objectives

The WISE Project will produce a sensitive mid-infrared (3.3 to 23 micron) survey of the entire sky. The primary science objectives for the WISE mission are to study the nature and evolutionary history of ultra-luminous IR galaxies (ULIRGs) and identify the most luminous galaxies in the universe, and measuring the space density, mass function, and formation history of brown dwarfs (BDs) in the solar neighborhood. WISE will also determine the radiometric albedos for almost all known asteroids, and study the luminosity function for very faint protostars and the evolution of circumstellar disks. The WISE survey will provide an essential database for testing theories of the origins of planets, stars, and galaxies, and an important catalog for the James Webb Space Telescope (JWST). WISE has four bands denoted bands W1 - W4, at 3.3, 4.7, 12, and 23 microns.

2.2 End Item Science Products

The WISE Project's Science Products are:
A source catalog for the entire sky, and an image atlas for the entire sky. The specifications for these science products are given in the WISE Level 1 and Level 1.5 requirements. Table 2 summarizes the Level 1 and 1.5 performance requirements relevant to the calibration plan. Sky coverage is addressed in the WISE survey plan, while catalog completeness and reliability are discussed in the WSDC Functional Requirements Document. Table 2 summarizes the Level 1 performance requirements.

DOORS Reqmt #	Baseline Requirement	Verification Method
(5)	The WISE survey shall consist of images in four filter bandpasses with wavelength centers within 10% of 3.3, 4.7, 12, and 23 micrometers.	D
(6)	The WISE survey shall obtain four or more independent exposures in each filter over at least 95% of the sky.	A, D
(4)	The WISE survey shall achieve a signal to noise ratio (SNR) of 5 or more on 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, where the noise is limited to zodiacal foreground emission, instrumental effects, source photon statistics, and unresolved extragalactic sources.	A
(12)	The root mean square error in relative photometric accuracy of the WISE catalog shall be better than 7% in each band for unsaturated point sources with SNR > 100, 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.	A, D
(13)	The root mean square error in WISE catalog positions with respect to 2MASS catalog positions shall be less than 0.5”, for sources with SNR > 20 in at least one WISE band, 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.	A, D
L1.5SRD-	The Band 1 passband shall be from 2.8 micrometers to 3.8	A

33	micrometers. The short wavelength edge of this band may be increased to as much as 3.2 micrometers if necessary, with the understanding that narrowing this band decreases margin on sensitivity.	
L1.5SRD-34	The Band 2 passband shall be from 4.1 micrometers to 5.2 micrometers.	A
L1.5SRD-35	The Band 3 passband shall be centered at 12 micrometers with a bandwidth between 6 micrometers and 9 micrometers.	D
L1.5SRD-36	The Band 4 passband shall be from 20 micrometers to at least 25 micrometers, with a goal of greater than 26 micrometers.	A,D
L1.5SRD-77	The Band 1 facility sensitivity allocation without confusion noise shall be 0.102 mJy.	A,T
L1.5SRD-78	The effective Band 1 rss confusion noise sensitivity allocation shall be 0.063 mJy.	A
L1.5SRD-75	The Band 2 facility sensitivity allocation without confusion noise shall be 0.147 mJy.	A,T
L1.5SRD-76	The effective Band 2 rss confusion noise sensitivity allocation shall be 0.062 mJy.	A
L1.5SRD-81	The Band 3 facility sensitivity allocation without confusion noise shall be 0.551 mJy.	A,T
L1.5SRD-82	The effective Band 3 rss confusion noise sensitivity allocation shall be 0.344 mJy.	A
L1.5SRD-79	The Band 4 facility sensitivity allocation without confusion noise shall be 2.42 mJy.	A,T
L1.5SRD-80	The effective Band 4 rss confusion noise sensitivity allocation shall be 0.95 mJy.	A
L1.5SRD-69	The ratio of the integrated system out-of-band response to integrated system in-band response for Band 1 shall be less than 1% assuming an A0 star source, and less than 1% assuming an 800K brown dwarf source, with a goal of less than 1% assuming a B0 star source	A,T
L1.5SRD-70	The ratio of integrated system out-of-band response to integrated system in-band response for Band 2 shall be less than 1% assuming an A0 star source, and less than 2% assuming a Class 2 circumstellar disk source, with a goal of less than 1% assuming a B0 star source	A,T
L1.5SRD-71	The ratio of integrated system out-of-band response to integrated system in-band response for Band 3 shall be less than 1% assuming an A0 star source, and less than 1% assuming a Class 2 circumstellar disk, with a goal of less than 1% assuming a B0 star source	A,T
L1.5SRD-72	The ratio of integrated system out-of-band response to integrated system in-band response for Band 4 shall be less than 1% assuming an A0 star source, with a goal of less than 1% assuming a B0 star source.	A,T
L1.5SRD-45 and 48	The relative photometric accuracy requirement shall be achieved for inertial point sources no less bright than: 0.11 Jy for Band 1 0.06 Jy for Band 2 0.25 Jy for Band 3 0.3 Jy for Band 4	A,D

Table 2: Level 1 and 1.5 performance requirements for WISE science data. D=demonstration; A=analysis; T=test.

2.3 Mission Phases

2.3.1 Development

The WISE Development Phase includes Lifecycle phases B, C, and D through the Flight-system assembly and test. The emphasis is on the design and development of the WISE flight hardware and software and the WISE ground data systems.

2.3.2 Launch

The WISE Launch Phase includes that portion of phase D that integrates the Flight-system to the launch vehicle, the loading of the hydrogen, the servicing of the Flight-system on the Launch vehicle, the actual launch through the separation of the Flight-system from the vehicle.

2.3.3 In-Orbit Check-out (IOC)

The WISE IOC phase includes the last portion of the Lifecycle phase D and picks up after Flight-system separation from the launch vehicle. This phase includes all the Flight-system set-up and check-out activities including cover deployment, scan mirror to spacecraft pointing alignment, and calibration. WISE's IOC phase is described in the WISE IOC Plan (JPL/38048).

2.3.4 Survey Operations

The WISE Mission Survey Phase includes that portion of the lifecycle phase E for which the flight system is operational and actively collecting science data (~6 months). The emphasis is to operate the flight system and successfully downlink all the required science data.

2.3.5 Science Operations

The WISE Science Operations phase includes all of the Lifecycle phase E and overlaps with the Survey phase. The Science Operations task is to process the Flight-system science data into the WISE science products, validate those products, release the products to the science community and archive the data.

2.4 Flight System Description

See the WISE Facility Requirements Document (JPL/D30564).

2.5 Science Operations Description

See the WISE MOS Requirements Document (JPL/D30571).

3 Description of Calibration Process

The process described in this section will lead to the delivery of the WISE Catalog and Image Atlas as well as verification of the terms described in the error budgets in Section 5. By following the plans described in this section, the Level 1 and 1.5 requirements on the WISE science data products for sensitivity, photometry, and astrometry will be met (assuming the rest of the elements of the WISE system perform to their specifications). The processes described in this section depend on the input of the Calibration Receivables Lists, which are given in Section 4. Raw WISE data frames, once transmitted to the WISE Science Data Center (WSDC), will be processed for single orbits and for multiple orbits for each unique sky position. The WISE calibration process consists of measurements made before and after launch, combined with the software tools necessary to produce the final science data products. We will obtain the data needed to produce the final calibrated images and extracted source lists through a combination of ground-based measurements, measurements made during the in-orbit checkout (IOC) phase, and measurements derived from the survey itself. We have collated all these items into the Calibration Receivables Lists. A general description of the measurements made on the hardware both before and after launch are provided in this Plan; however, the specific descriptions of the ground-based payload tests are given in the SDL Payload Electro-Optical Characterization Plan (SDL/05-191); the detailed descriptions of the calibrations to be performed during IOC can be found in the WISE IOC Plan (JPL/38048); and

the descriptions of measurements made from the survey data and the specific details of the WISE data processing pipeline can be found in the WISE Project Data Management Plan.
Before WISE launches, many aspects of the hardware will be characterized, including dark frames, read noise, flat fields, linearity and saturation, image quality (including focus and band-to-band alignment), stray light, scan mirror alignment and linearity, alignment, system relative spectral response, out-of-band blocking, EMI/EMC compatibility, etc. Focus will be set on the ground; there is no focus mechanism on WISE. A network of standard stars will be developed that will incorporate measurements from the Spitzer Space Telescope, 2MASS and stellar atmosphere models. After WISE launches, we will enter a one month IOC phase. The IOC is roughly divided into two equal periods, pre- and post-cover ejection. Before the cover is ejected, we will obtain dark exposures in bands W1 and W2, and we will measure how close to the South Atlantic Anomaly the spacecraft may be and still acquire usable data. After the cover is ejected, we will obtain first light exposures, synchronize the scan rate of the scan mirror to match that of the spacecraft, measure detector linearity, and update our flat field calibrations, stray light maps, and models of detector droop and latent behavior. Once IOC is completed, we will begin the six month survey phase.
After science data are acquired during the survey phase, they will be downlinked and transmitted for data reduction. As part of the reduction process, the data will be calibrated according to the steps described below. Producing the source catalog can be broken down into three steps: constructing the processed images; detecting and characterizing sources; and third, calibrating the extracted source photometry.

3.1 Calibration Process

3.1.1 Instrumental Image Calibration

The purpose of this stage of the image processing is to remove detector and optical system signature from the raw imaging data.

1. Mask raw frame using *a priori* bad-pixel mask and flag additional pixels for new broken and saturated pixels tagged in downlink, and neighbors for possible IPC effects.
2. Convert raw frame pixel values from 16-bit to 32-bit floating point and add 0.5 DN to allow for truncation bias in on-board SUR-slope estimate.
3. Fit and subtract reference pixel offsets (specific bands TBR).
4. Apply global droop corrections - including 2nd order row/column dependent droop (specific bands TBR).
5. Apply bias/dark subtraction using initial dark from ground/IOC calibration.
6. Apply non-linearity correction (specific bands TBR).
7. Divide raw image with unit-normalized pixel responsivity map (flat-field).
8. Subtract zero-normalized sky illumination correction from flattened image.
9. Mask new hot/low-responsive pixels using local frame statistics.

3.1.2 Astrometric Calibration

This process derives the transformation from pixel coordinates to right ascension and declination for each set of 3.3, 4.7, 12 and 23um images.

1. Detect SNR>7 (TBR) sources from individual image frames. Determine the centroid of each source detection in image pixel coordinates (x(b),y(b)).
2. Positionally correlate extracted sources in four bands in pixel coordinates using *a priori* band-to-band offsets (bandmerge), determine position uncertainty variance-weighted average source position in "universal-pixel" coordinate system (u_x,u_y).

3. Convert image universal-pixel coordinates to preliminary equatorial coordinates using spacecraft pointing data, *a priori* boresight correction and *a priori* distortion correction (ra_0,dec_0).
4. Positionally correlate extracted source list with 2MASS PSC astrometric reference database using preliminary equatorial coordinates.
5. Derive solution for u_x,u_y -> ra,dec conversion, incorporating terms for actual band-to-band offsets and actual focal plane distortion, etc.
6. Use position transformation to derive equatorial position for each band-merged extraction.
7. Derive corrected WCS information for each band image and apply to each image FITS headers.
8. Output boresight, band-to-band and distortion solutions to astrometric database.

Astrometric calibrations will be updated as necessary for images produced from combined multiple-orbit data.

3.1.3 Photometric Calibration

The purpose of this process is to convert brightness measurements in instrumental units (data numbers, or DN) to to relative physical units useful for scientific analysis. All WISE source brightnesses will be reported in magnitudes relative to measurements of a network photometric standard stars of known brightness in the four WISE bands. This is accomplished by:

1. Conduct photometric measurements of all sources detected on the individual image frames in all four bands from a single WISE orbit (TBR).
2. Positionally correlate the band-merged source extraction list from each orbit with the list of objects in the standard star network.
3. Derive a preliminary photometric zero point offset for each band in each orbit (zp(b)) by
    a. Computing the linear relationship between the instrumental and "true" magnitudes for the standard stars found in each orbit's extracted source list
    b. Incorporating a color-term in the fit between instrumental and “true” magnitudes, if necessary. (All WISE source photometry will be expressed in the natural WISE system, so color-terms in the zero point fit may not be required)
4. Apply the photometric zero point offset corrections to instrumental magnitudes measured for all sources in orbit to generate preliminary calibrated frame source magnitudes.
5. Optionally Positionally correlate sources falling within in-scan and cross-orbit overlap regions of frames in orbit/group of orbits.
6. Measure zero point variations on sub-orbit timescales by computing the mean magnitude differences of sources detected in the cross-orbit overlap regions of frames taken in adjacent orbits..
7. Apply time-dependent zero point corrections to the preliminary calibrated source magnitudes to generate final frame source brightness measurements.
8. Derive and apply photometric zero point magnitude for each image frame using the source measurements and insert into image FITS header.
9. Use the measured relative spectral response (RSR) of the instrument to provide users with the conversion of WISE magnitudes to flux density (i.e. the flux density values corresponding to zero magnitude).

4 Calibration Receivables List

In order to perform the calibration process given in Section 3, certain data products are required from various phases of the mission. These include test data and analyses which will be performed at the payload and system level, as well as during IOC and normal operations. They also include theoretical astrophysical models.

4.1 Pre-flight calibration receivables

Table 3 below gives the pre-flight receivables, responsible parties, and method by which each item will be verified (test, analysis, demonstration, etc.). It also cross-references the test procedures with which each item is verified.

Each item in Table 3 has been assigned to a Cognizant Scientist. The Cognizant Scientists' roles are to work with the cognizant engineers and with WISE test, IOC, and survey data to provide independent insight into their assigned area.

Item	**Band**	**Verification Method**
Detector responsivity maps (flat fields)	All	A, T
Detector dark images	All	A, T
Read noise maps	All	A, T
Droop calibration	All	A, T
Saturation limits	All	A, T
Inter-pixel capacitance and crosstalk	All	A, T
Dynamic range/linearity	All	A, T
Saturation flag verification – verify that pixel values are set to correct fiducial value when the A/D saturates Also, refine saturation flag thresholding.	All	A, T
Detector QE maps	All	A, T
Latent image characteristics (after saturation, annealing, and various flux levels): dark latents (i.e. low response against bright backgrounds) and bright latents (bright against dark background)	All	A, T
Latent image characteristics (after radiation)	All	A, T
Bad pixel maps	All	A, T
Time dependence of gain maps, darks, linearity, bad pixel maps, read noise	All	A, T
Detector idiosyncrasies	All	A, T
Post-annealing behavior of gain maps, darks, linearity, bad pixel maps, latents, read noise	3, 4	A, T
Final system alignment	All	A, T
Scan mirror characteristics – stability, linearity, and repeatability of starting/stopping positions	All	A, T
Transmission/reflectance curves for all optical elements – in band	All	A, T
Transmission/reflectance curves for all optical elements – out of band	All	A, T
Optical ghost analysis – out of field	All	A
Optical ghost analysis – in field	All	A
Bright source artifacts	All	T
Focal plane distortion map (with scan mirror and averaged over all nominal mirror positions)	All	A, T
Theoretical PRF across arrays	All	A
Temperature stability of flat fields, dark currents, etc.	All	A, T
Vignetting maps	All	A, T
Standard star network – astrometric	All	A, D
Standard star network – photometric	All	A, D

Table 3: Pre-flight receivables.

4.1.1 Standard star network requirements

In order to compute photometric zero points, a network of standard stars must be established in regions that are observed nearly every orbit by WISE. These stars must have accurately known fluxes in the WISE bands and positions. This section establishes the requirements on the standard star network.

4.1.1.1 Locations

The primary standard stars must be located at ecliptic latitude |b| > 89.61 degrees. This region, near the north and south ecliptic poles, will be observed nearly every orbit, modulo downlink and yaw maneuvers.

4.1.1.2 Number

There must be at least 8 standard stars equally distributed between the WISE FOVs at the NEP and SEP to provide routine zero point determinations for WISE bands 1, 2, and 3, and at least 7 band 4 standards as close as possible to the ecliptic poles. In addition, a small number of "red calibrators" (a combination of ULIRGS and asteroids) will be established during IOC. The ULIRGS will be selected for their proximity to the ecliptic poles.

4.1.1.3 Flux

The standard stars shall have predicted flux densities of in the ranges (in mJy) 7-110, 9-60, 36-250, 145-2000 for bands 1, 2, 3, and 4, respectively.

4.1.1.4 Spectral Type

The standard stars shall preferably be Milky Way stars of known spectral type to facilitate atmospheric modeling, preferably in the ranges A0V-A5V or K0-M0III.

4.1.1.5 Isolation

Sources should be isolated and unresolved by WISE. There shall be no sources with fluxes greater than 5% within TBD arcsec of each WISE calibration object. We will be better able to determine the separation radius when we have a detailed characterization of the arrays, including effects such as mux bleed, pull-downs, glints, ghosts, etc., as well as the detailed structure of the PSF. The minimum separation radius for the IRAS KIII network was 6 arcmin; however, the WISE radius will be determined based on the examination of the ground and IOC measurements of the individual channel characteristics.

4.2 IOC/Survey mode calibration receivables

These include calibration deliverables to be derived using analysis of on-orbit measurements. Table 4 below gives the IOC/survey mode receivables, responsible parties, and method by which each item will be verified (test, analysis, demonstration, etc.).

Item	Band	Verification Method
Flat field corrections from zodi background gradients	All	A, T
Flat field corrections from dark sky medians	All	A, T
Low frequency flat field corrections from point source residuals	All	A, T
Non-linearity calibration using source mapping	All	A, T
Droop calibration	All	A, T
Point source photometric residuals	All	A, T
Scan mirror to spacecraft rate synchronization residuals	All	A, T
Stability of flat fields, dark offsets (from reference pixels), illumination corrections (sky + instrument) vs. time	All	A, T
Stability of flat fields, dark offsets (from reference pixels), illumination corrections (sky + instrument) after annealing	3, 4	A, T
Illumination corrections (sky + instrument) from sky medians	All	A, T
Latent image behavior (bright + dark latents)	All	A, T
Detector idiosyncrasies	All	A, T
Updates to bad pixel maps	All	A, T
Diffraction spike map	All	A, T

Ghost and scattered light behavior	All	A, T
Updated standard star network (using on-orbit measurements)	All	A, T

Table 4: IOC/survey mode receivables.

5 Error Budgets

To meet the Level 1 and 1.5 requirements specified above, we created error budgets based on analytical and experimental arguments. These error budgets provide a breakdown of the systematic and random errors that contribute to photometric errors and astrometric errors. They are used to help determine which quantities need to be measured and which analyses need to be performed at all mission phases to ensure delivery of a useful WISE Catalog and Image Atlas. These budgets will be updated throughout the mission as predictions are replaced with experimental data and improved analyses are performed. The photometric and astrometric error budget calculations are maintained in two Excel spreadsheet files, which are maintained in the WISE Docushare library. The most recent versions are PhotErrorBudget09_14_07.xls and AstroErrorBudget09_14_07.xls. The instrument portion of the sensitivity budget calculation is maintained by the Payload Systems Engineer at SDL as a Mathcad calculation; the top-level budget containing all terms (including astrophysical) are maintained at JPL using an Excel spreadsheet.

5.1 Sensitivity

Definitions:
Speed of light: c
Planck's constant: h
Object spectrum in W/(m^{2}Hz)) at frequency ν: O(ν)
Object spectrum in W/(m^{2}µm)) at wavelength λ: O(λ)
Object spectrum in photons/(m^2 µm s) at wavelength λ: N(λ)
Zodiacal background (e-/sec/pix): B
Dark current (e-/sec/pix): I_d
Read noise (e-/pix): R_n
Integration time (s): t
Number of noise pixels (pix): N_p
Number of frames (dimensionless): N_f
Relative Spectral Response (number of photoelectrons detected per object photon collected by WISE at wavelength λ): RSR(λ)
Collecting area of WISE in m^2: A
Total signal after Nf frames (e-): S
Total noise in Nf frames for a source covering Np pixels: N
The measured signal is given by:

(1) $S = AtN_f \int N(\lambda) RSR(\lambda) d\lambda$

N(λ)=O(λ)/(hν)
= λO(λ)/(hc)
= νO(ν)/(hc)
= O(ν)/(hλ)

Therefore, the measured signal is:

(2) $S = AtN_f \int (1/h\lambda) O(\nu) RSR(\lambda) d\lambda$

The noise (excluding confusion noise) N produced over the Np pixels that are covered by the source in Nf frames is the uncorrelated sum (root sum square) of the read noise and the background and dark current shot noise.

(3) $N = \sqrt{N_p N_f (R_n^2 + t(B + I_d))}$

The signal to noise ratio SNR is then:

(4) $SNR = At\sqrt{N_f / (N_p (R_n^2 + t(B + I_d))} \int (1/h\lambda) O(\nu) RSR(\lambda) d\lambda$

Because the ratio of WISE bandpass to central wavelength is up to 0.75 (7.5 to 16.5 μm for WISE band 3 or W3), sensitivity calculations need to specify spectral variations across the band.

We assume a source spectrum which is constant in N(λ). This is equivalent to a spectrum with O(ν) ~ ν^{-1} or, O(ν) = kλ. Then:

(5) $SNR = (k/h) At\sqrt{N_f / (N_p (R_n^2 + t(B + I_d))} \int RSR(\lambda) d\lambda$

To compare with sensitivity requirements, the flat N(λ) source photon spectrum which produces SNR = 5 needs be converted to flux in Janskys. This conversion is done at the central wavelengths of 3.3, 4.65, 12, and 23 μm. We also reduce the sensitivity requirements by the effective rss confusion noise. Thus the sensitivity requirement is satisfied for SNR = 5:

(6) $k_1 < 0.102$ mJy / 3.3 μm
$k_2 < 0.147$ mJy/ 4.65 μm
$k_3 < 0.551$ mJy/ 12 μm
$k_4 < 2.42$ mJy/ 23 μm

where

(7) $k_i = 5h\sqrt{N_{pi}(R_{ni}^2 + t(B_i + I_{di}))/N_f} \bigg/ At\int RSR_i(\lambda) d\lambda$

Substituting t=8.8s, N_f=8, A=0.101 m^2 from below, and h=6.626 x10^{-2} x10^{-32} J-s and recalling that 1 μJy = 10^{-32} W/(m^2 Hz) = 10^{-32} J/ m^2 we have:

(8) $k_i = (0.373 \mu Jy/\mu m)\sqrt{N_{pi}(R_{ni}^2 + 8.8(B_i + I_{di}))/8} \bigg/ \int RSR_i(\lambda) d\lambda$

Estimates as of Sept. 2007 for these terms (see below) give (TBR) 0.06,0.1,0.5, and 2.4 mJy in bands 1 - 4 respectively.

5.1.1 Background

The WISE zodiacal background surface brightnesses were derived using COBE/DIRBE data, specifically the "FIZZ3P" model described in Wright 2001, IAU Symp. 204, p. 157 (astro-ph/0106412). Additional details are provided in the appendix to Wright 1998, ApJ 496, 18.

The values used for 90 degree elongation on the ecliptic are: 0.165, 0.782, 32.3, and 69.7 MJy/sr at 3.5, 4.85, 12, and 25 microns. These agree fairly well with those in Table 19 of Leinert et al 1998, A&A Supp, 127, 1. A spline was fit in log-log space to these values to allow the backgrounds B(ν) in the WISE bands to be calculated (TBR). The actual background values are calculated using a variant of equation (2)

(9) $B_i = AtN_f \Omega_{IFOV} \int (1/h\lambda) B(\nu) RSR_i(\lambda) d\lambda$

where Ω_{IFOV} is the pixel solid angle (2.75^2 arcsec^2 for bands 1 -3, 5.5^2 arcsec^2 .for band 4 due to 2 x 2 pixel binning).

As of June 2007, the estimated backgrounds on the ecliptic are 7, 19, 1950, and 5650 e-/s for WISE bands 1 through 4. These values will be updated using IOC data.

5.1.2 Collecting area and Integration Time

We use SSG's final design values of 40 cm diameter and 19.5% central obscuration, which gives A = 0.101 m^2.

The WISE sampling sequence consists of a reset and sample followed by eight additional readouts, each taking 1.1 seconds to sample the full array, for a total integration time of t = 8.8 seconds per pixel. An additional 1.1 seconds is needed for the final readout, and the scan mirror flies back during another 1.1 second interval, giving a total frame cycle time of 11.0 seconds.

5.1.3 Relative Spectral Response

The relative spectral response RSR(λ) is the response of WISE as a function of wavelength in electrons per photon incident on the WISE entrance aperture from the object, and includes the transmission and reflection of optics, dichroic beamsplitters, filters T(λ), and the quantum efficiency of the detector QE(λ).

(10) $RSR_i(\lambda) = T_i(\lambda) QE_i(\lambda)$

5.1.3.1 Transmission and Reflection

The WISE optical system (see Figure 1) include 13 reflections prior to the dichroic beamsplitters and filter for each focal plane, so high reflectivity is important.

Figure 2 shows the measured reflectivity (from a witness sample) of the WISE gold coating after 13 reflections. We also include 1% loss due to contamination. The dichroic beamsplitter and filter portion of the transmission is shown in Figure 3.

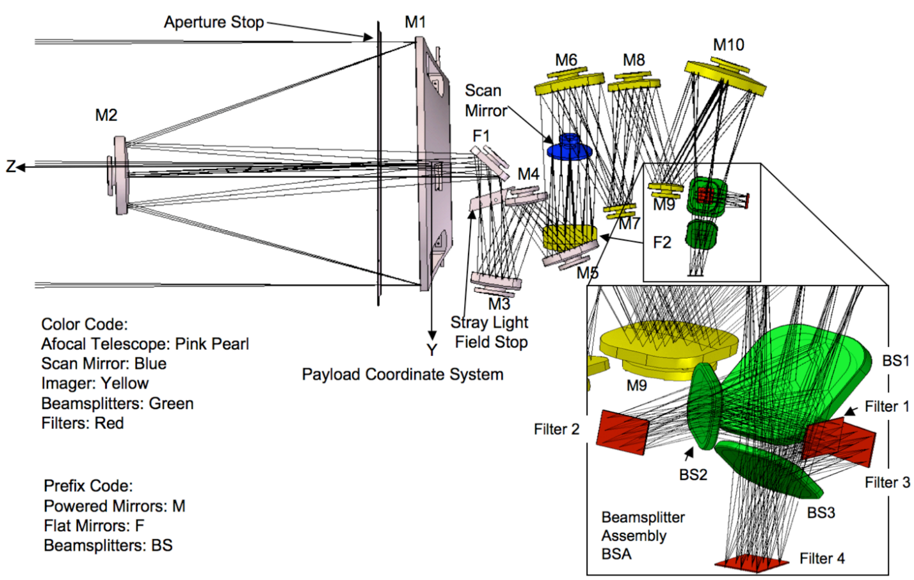

Figure 1: WISE Optical Layout, with inset showing detail of beamsplitter assembly.

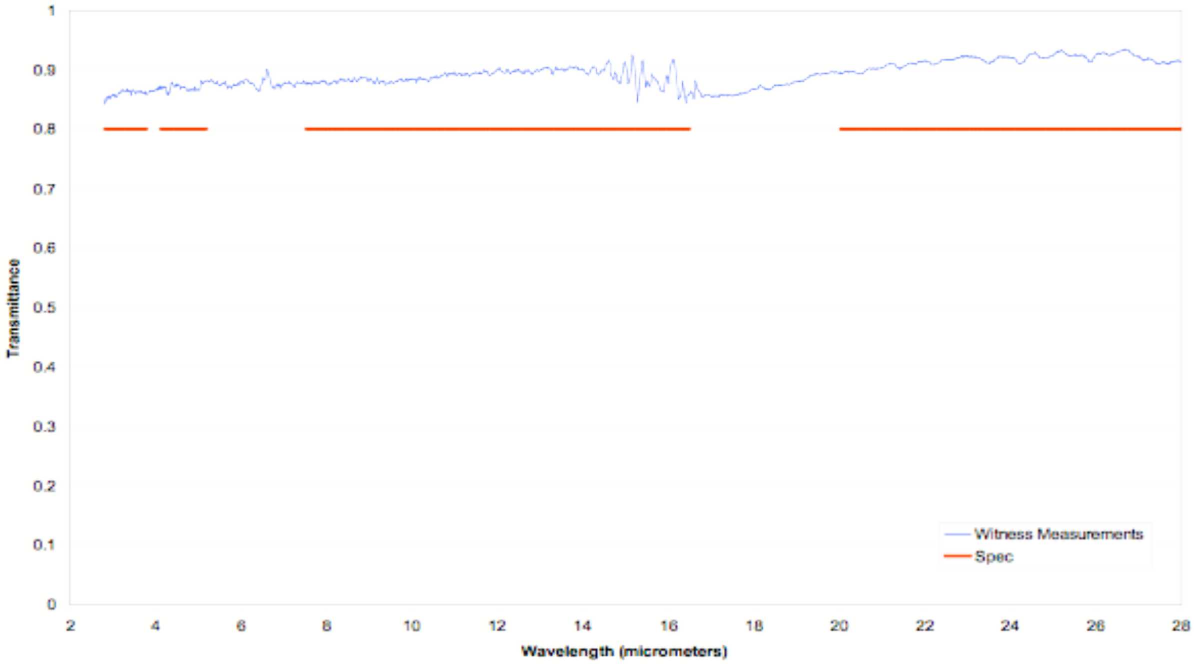

Figure 2: Transmission of WISE reflective optics, based on measurements by SSG of the WISE gold coating on a witness sample. Red lines show the 80% specification.

5.1.3.2 Quantum Efficiency

DRS and Teledyne have provided the QE from PEC ("process evaluation chip") measurements for WISE detector material. WISE uses a ZnSe antireflection (AR) coating which provides slightly better QE in band 4, and a ZnS AR coating for band 3. Measurements of the flight detector quantum efficiencies through narrow band filters at selected wavelengths will be obtained at DRS by October 2007.

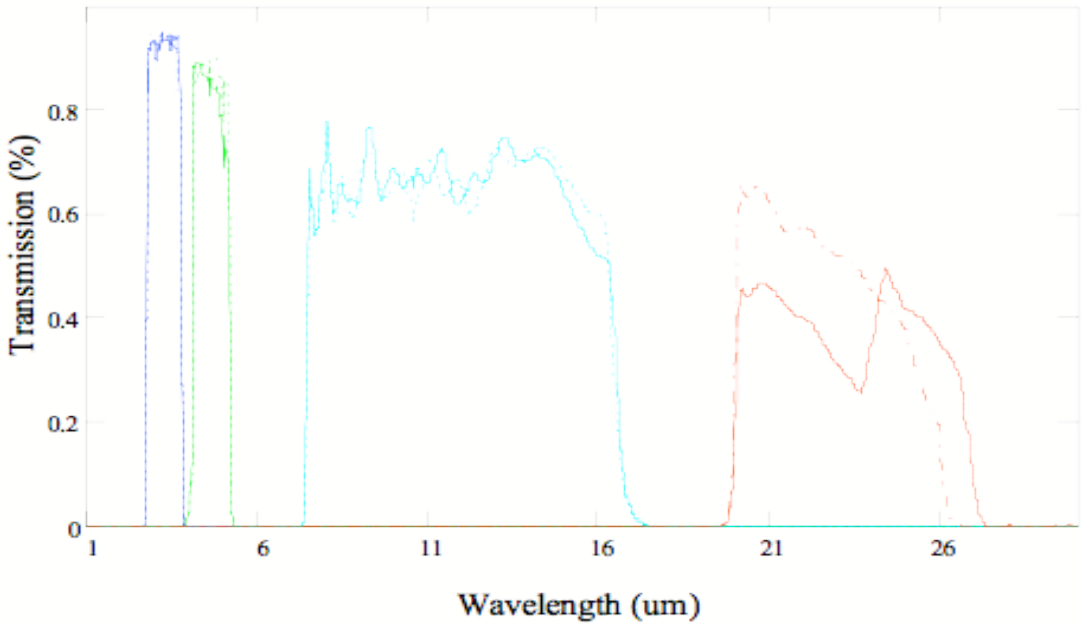

Figure 3: WISE transmission including both reflective optics and dichroic/beamsplitters (see figure 1). The dashed lines show the predicted transmission values from the March 2006 Payload CDR, while the solid lines show the estimates as of April 2007.

The WISE RSRs will be measured directly at SDL as described in section 6 of the WISE Payload Electro-Optical Characterization Plan (SDL/05-091).

5.1.4 Noise Pixels

Noise pixels are a measure of image quality. The number of noise pixels is one over the sum of the inverse square of the point source function including pixel response, or PRF, where the sum of the PRF has been normalized to one. Section 5 of the WISE Payload Electro-Optical Characterization Plan (SDL/05-091) provides an extensive discussion of image quality tests during payload integration.

During IOC, the rate of change of direction of the WISE spacecraft must be tuned to match the payload scan mirror. This will be accomplished by taking a grid of spacecraft scan directions and rates and determining the combination which produces the smallest harmonic mean number of noise pixels over the WISE field. The harmonic mean is given by

$$1 \Big/ n \sum (1/N_{pj})$$

where N_{pj} is the measured number of noise pixels for star j, and n is the number stars. Three progressively finer iterations of this calibration are planned for IOC. Additional details are provided in the IOC plan.

The allocations for mean noise pixels are 14.5, 18.2, 48.4, and 34.0 in WISE bands 1 through 4. Note that for band 4 2x2 binning is used, i.e. the effective pixel size is 5.5 arcsec to reduce the data rate by 18.75%.

5.1.5 Read Noise

Because of the very low background in band 1, read noise dominates sensitivity in that band. Measurements with flight-like electronics and flight detectors in their flight mounts are planned for October 2007. Additional measurements will be obtained during payload integration. As of June 2007, the estimated CDS read noises are 16 electrons in bands W1 and W2, and 75 electrons in bands W3 and W4.

5.1.6 Dark Current

Dark images for bands W3 and W4 must be measured on the ground before launch, since WISE has no cold shutter, and the cover will be too hot prior to ejection (bands 3 and 4 are predicted to be saturated). Since it is likely that the SDL MIC2 chamber will not be completely dark, the best dark measurements will come from DRS prior to delivery of the flight FPMA and flight electronics. Dark currents for bands W1 and W2 will also be measured on the ground at DRS; however, there will also be an opportunity to re-measure them on-orbit prior to WISE cover ejection during in-orbit checkout because the cover will be dark at these wavelengths. Ground dark measurements will be used to better predict performance and to understand any idiosyncratic behavior of the W1 and W2 detectors.

The first way a dark offset can affect WISE data is by changing the offsets on individual frames. This can be mitigated by either subtracting a dark frame known a priori from all images, or by subtracting off an offset frame derived from a median of a large number of images. The current plan is to subtract a sky illumination correction from all of the images prior to performing photometry on individual sources. This correction is constructed from a running trimmed average of a number of sky frames taken at a time similar to the frame being corrected. In principle, this should remove any offsets and structure, provided that they remain constant over the duration over which the sky is computed. Based on experience calibrating infrared imaging data from 2MASS, we estimate that ~50-100 frames will be necessary to filter out the sources from the images and obtain a good representation of the smooth sky illumination. However, the number of frames is only an estimate at present, and a larger number could be required. We therefore would like the dark current to remain stable to the levels we derive below for at least several hours. If the dark frames vary over this time interval, this will effectively add a false signal to our images that will degrade sensitivity and photometric precision. In this section, we will compute the level of stability that is required to keep losses of sensitivity less than 1% due to this effect.

5.1.6.1 Error in Flat Field Response

The second way a dark offset can affect our data is by inducing and error in the computation of the flat field response maps. Flat fields for WISE will be obtained initially via ground-based testing pre-launch. During on-orbit operations, the flat-field correction maps will be updated using measurements of the response to gradients in the zodiacal emission and the photometric residuals of point sources that are detected at different positions on the focal planes. A dark frame must be subtracted from the illuminated frames used to compute the flat field response. If the dark offsets are not well-known, these would result in an erroneous flat field correction being divided into the on-sky images. However, this effect turns out to produce a less stringent requirement on dark current knowledge than the need for stability does.

Definitions:

Allowable fractional error due to a particular term: P

Error in the flat field due to dark frame instability: E_{df}

Let us assume that the flat is constructed using the response to the gradient in the zodiacal background. An error in the flat will arise when we subtract the erroneous dark, and the error will be a fraction of the zodiacal background illumination per pixel, E_{df} /B. This error affects the estimated signal per pixel per frame, leading to an error N_d in the estimated total signal S after N_f frames of

$$N_d = \frac{E_{df}}{B} \frac{S}{N_f N_p} \sqrt{N_f N_p}\text{, or}$$

(11) $N_d = S\frac{E_{df}}{B\sqrt{N_f N_p}}$

We require that the error due to this term not exceed P * S, or

$N_d < PS$, or

$S\frac{E_{df}}{B\sqrt{N_f N_p}} < PS$, which simplifies to

(12) $E_{df} < PB\sqrt{N_f N_p}$

The following table summarizes the requirements that derive from this equation for all four bands, using the assumptions about values for the bands from SDL. We assume that we want no more than 1% photometric error from this term, or P=0.01.

Band	1	2	3	4*
Background (e-/sec/pix)	8	24	2200	1200
Read noise (e-/pix), assuming SUTR	19	19	55	55
Dark current (e-/sec/pix)	1	1	100	100
Noise pixels per source	10.3	14.05	37.6	28.1
Integration time (sec)	8.8	8.8	8.8	8.8
Number of frames	8	8	8	8
Required E_{df} from Equation (5) above (e-/sec/pix)	**0.7**	**2.5**	**382**	**1439**

Table 5: Requirements on dark current error Edf derived from flat field errors. *Band 4 is binned such that every 2x2 pixels become one. Therefore the background and noise pixels are 4x higher than the actual value per unbinned pixel (shown in the table).

5.1.6.2 Error Due to Dark Current Instability

Because the local sky level will be subtracted out during the image calibration process, it is actually dark current instability that will be detrimental to sensitivity and photometric accuracy. To verify that the dark current is actually stable to the levels we require, we must collect data over the timescale of interest.

5.1.6.2.1 Effect of Dark Current Instability on Sensitivity

We can compute the effects on sensitivity as follows. The noise N produced over the Np pixels that are covered by the source in Nf frames is the uncorrelated sum (root sum square) of the read noise and the background and dark current shot noise. If the dark current instability is Ed, then the erroneous signal produced by this term is

(13) $N_d = E_d t\sqrt{N_f N_p}$

The requirement to keep the error due to dark current instability is given by the desire to keep this error Nd small:

$N_d < PS$, which from Equation 12 gives

$E_d t\sqrt{N_f N_p} < P \cdot N \cdot SNR$ or

$E_d t\sqrt{N_f N_p} < P \cdot SNR\sqrt{N_p N_f (R_n^2 + t(B + I_d))}$, or

(14) $E_d < P \cdot SNR\frac{\sqrt{R_n^2 + t(B + I_d)}}{t}$

Variation in the dark current that is unaccounted for results in a loss of sensitivity. WISE's sensitivity requirements are based on 5-σ sources. We seek to avoid sensitivity loss greater than 1% due to dark current instability, or P=0.1 and SNR=1. Table 7 below summarizes the requirement on Ed stability for this case.

Band	1	2	3	4*
Background (e-/sec/pix)	8	24	2200	1200
Read noise (e-/pix), assuming SUTR	19	19	55	55
Dark current (e-/sec/pix)	1	1	100	100
Noise pixels per source	10.3	14.05	37.6	28.1
Integration time (sec)	8.8	8.8	8.8	8.8
Number of frames	8	8	8	8
Required Ed from Equation (11) above (e-/sec/pix)	**0.24**	**0.27**	**1.7**	**1.4**

Table 6: Requirements on dark current stability Ed derived from sensitivity requirements. *Band 4 is binned such that every 2x2 pixels become one. Therefore the background and noise pixels are 4x less than the actual value per unbinned pixel.

The need to avoid sensitivity losses greater than 1% drives the dark current stability requirement. We need to verify that the dark current does not change by the amounts specified in Table 3 over a time period of at least several hours: **~0.25 e-/sec for the MCT arrays, and 1.5 e-/sec for the Si:As arrays.** Since the read noise is significantly higher than this dark current stability for all WISE bands, we will need to collect many frames to be able to measure the dark current stability. The number of frames necessary to collect is given by

(15) $N_{frames} = \left(\frac{R_n}{F I_d t} \right)^2$ where F is the fraction of the dark current to which the read noise must be reduced in order to adequately measure I_d. Assume F=0.1. Thus, for bands W1 and W2, if we assume that the dark current stability requirement is 0.25 e-/sec/pix, then we need ~2500 frames of data, or 6 hours' worth, to verify stability at that level (assuming that read noise is ~11 e- SUTR). For bands W3 and W4, if we need a dark current stability of ~1.5 e-/sec/pix, which translates to ~1700 frames, or 4 hours of data.

We plan that DRS will take 4 hours worth of dark data for all the flight arrays. We can also use this longer term dataset to look for time-variable noise sources such as popcorn noise, and possibly the banding seen in the Si:As arrays.

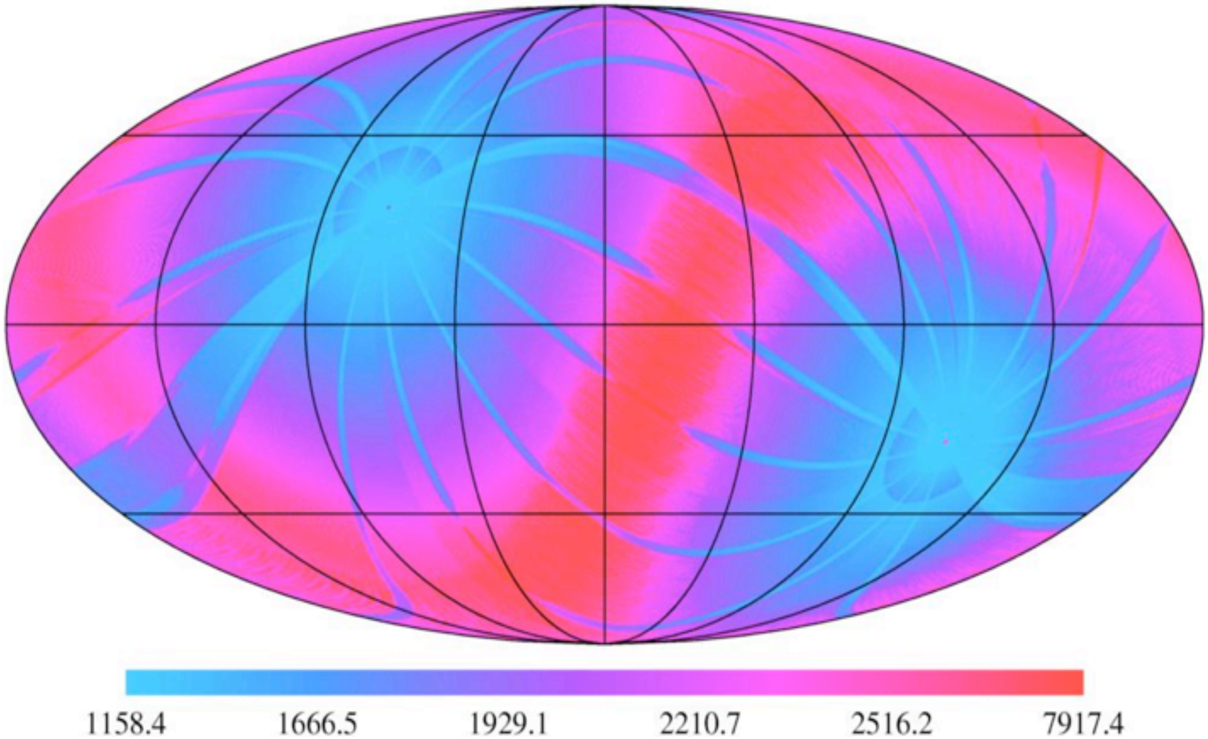

Figure 4: Variation in Band 4 sensitivity on the celestial sphere, plotted in Galactic coordinates, for the baseline survey including safing events and the loss of data due to proximity to the moon and SAA. Redder areas have poorer sensitivity because of fewer coverages and more zodiacal background on the ecliptic (the red S-shaped band) while the ecliptic poles have the best sensitivity (bluer areas).

5.1.7 Number of frames

We assume N_f = 8. In a nominal 6 month survey, WISE will obtain 8 or more repeats for 99.5% of sky after eliminating data compromised by the South Atlantic Anomaly (SAA), and data within 15 degrees of the moon. A conservative SAA contour was used, based on the 100 protons per cm^2 per second contour at 600 km altitude (the actual 530 km altitude is more benign), which should affect less than 1% of the pixels in a frame (assuming 10 pixels per proton). Stray light analyses show data should not be degraded 15 degrees from the moon, but stray light is typically somewhat uncertain. Calculations for > 20 degree moon avoidance show only a small (less than 1%) decrease in the percentage of sky with 8 or more repeats, (assuming replanning the survey based on the empirical stray light results from IOC). For a nominal baseline (6 month survey) mission WISE expects to obtain 9 or more repeats over 96.5% of the sky, still meeting the 95% sky coverage requirement.

There is an additional improvement as the number of repeats increases at higher ecliptic latitude, due to the lower background (see Figure 4).

The effective number of repeats is also proportional to the good pixel fraction. The WISE Science Data Center has simulated the effect of this using measured bad pixel fractions, and these show only a small overall effect.

5.1.8 Confusion

The allocations for effective rss confusion are specified in Table 2. These allocations are based on Spitzer data and simulated for WISE images. Confusion is affected by the image quality and by details of the photometry algorithm, and further simulations based on the pipeline developed by the WISE Science Data Center are planned prior to launch. Confusion noise will be assessed using WISE survey data.

5.2 Relative Photometric Error

The Level 1 requirement states that the WISE catalog shall have <7% relative photometric accuracy for SNR > 100 (< 10% for the minimum mission); see Table 2.

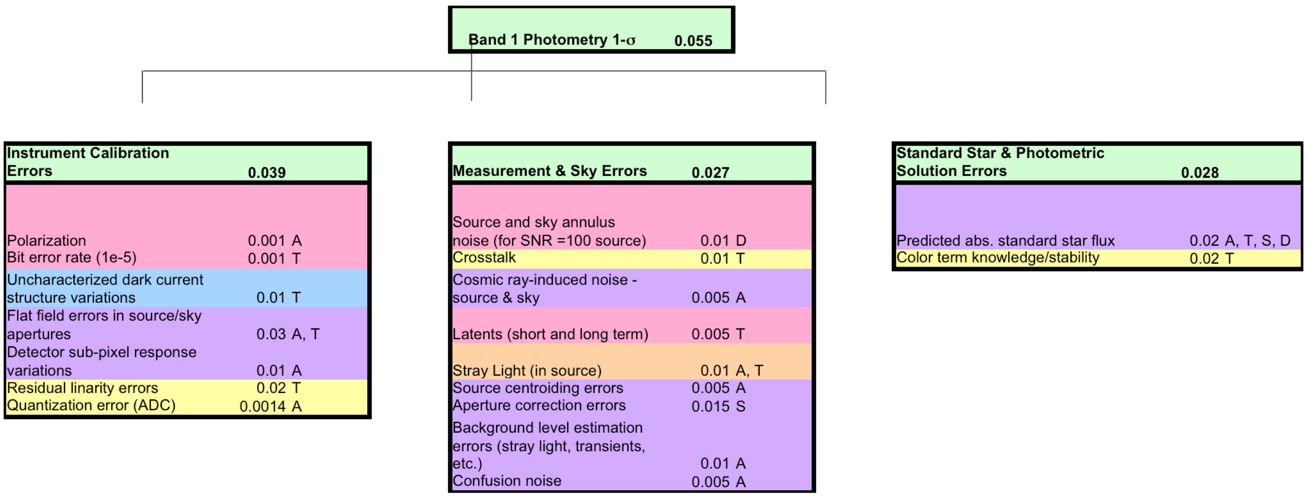

Figure 5: The relative photometric error budget for Band 1.

Figure 5 below shows the detailed breakdown of the photometric error for band 1, including instrumental, measurement, and photometric zero point terms.

5.2.1 Instrumental Calibration Errors

5.2.1.1 Polarization

WISE is not designed to detect polarization. The S and P polarizations of all four WISE channels are given in the following figures. The plots were generated from a mix of experimental data taken on the actual flight hardware and theoretical models validated by scans of witness samples. Although WISE has non-negligible polarization, particularly in bands W2 – W4, most astrophysical sources have less than a few percent polarization. When we consider the ensemble of the 300e6 sources that will be in the WISE catalog, the overall effect of changes in photometric accuracy due to polarization of the WISE optical system is negligible. However, individual astrophysical sources such as star formation regions can have polarizations as high as ~30% (Dyck & Lonsdale 1981). Observers will need to be aware of the WISE polarization, and an explanation (including the axes of polarization) will be written in the Explanatory Supplement that is published with the catalog.

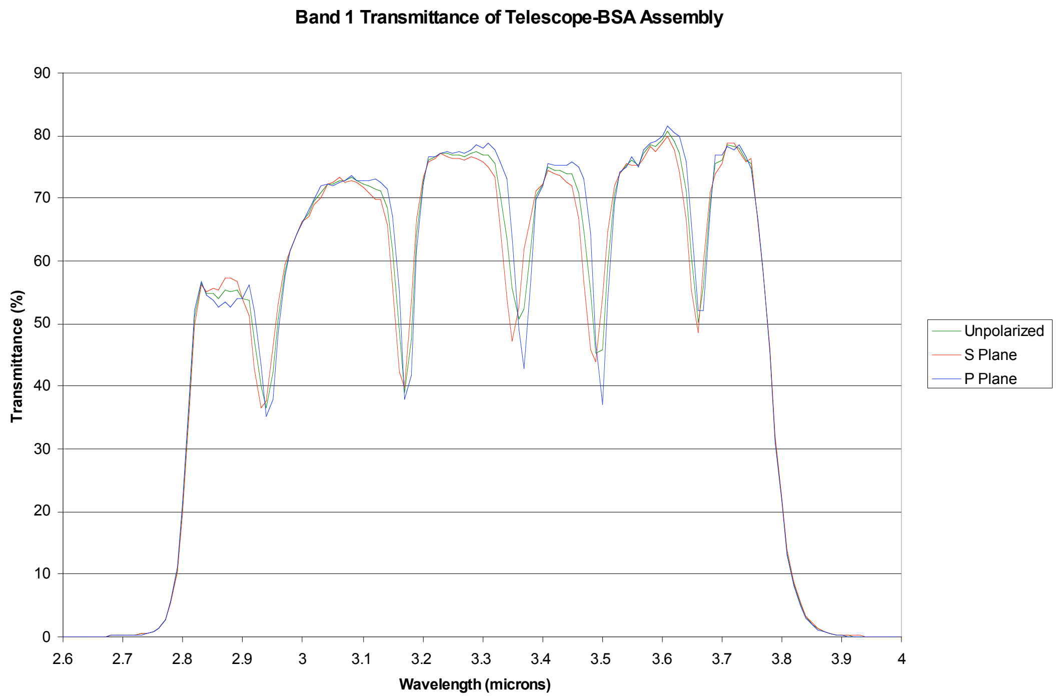

Figure 6: S and P polarization of the WISE optical system in band W1.

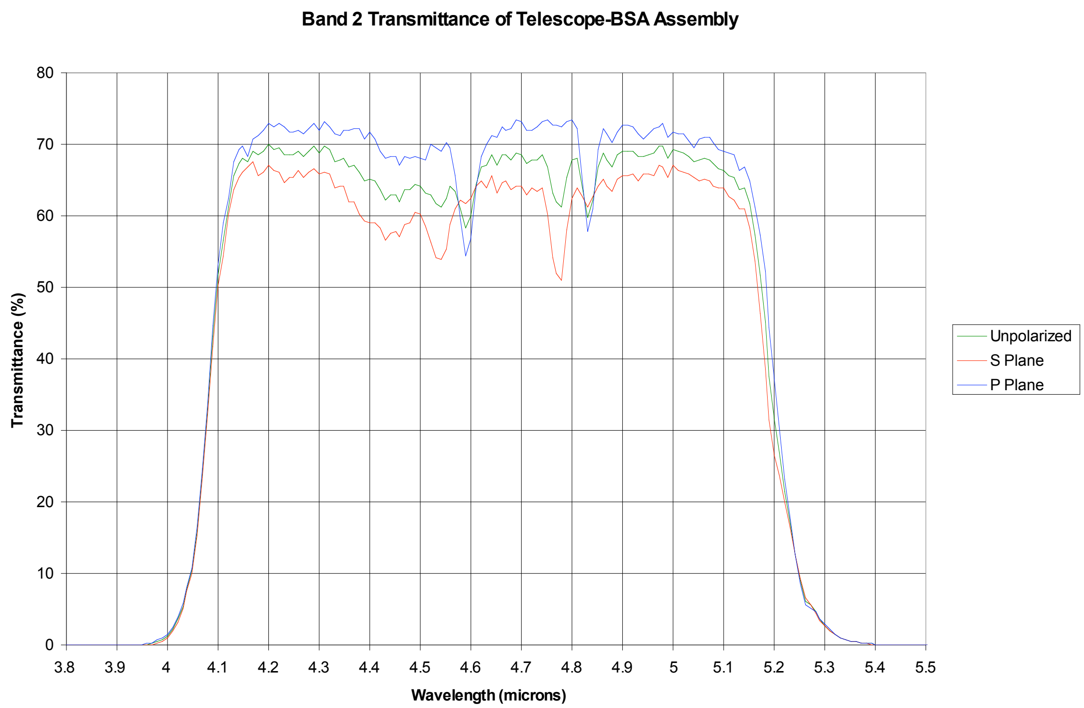

Figure 7: S and P polarization of the WISE optical system in band W2.

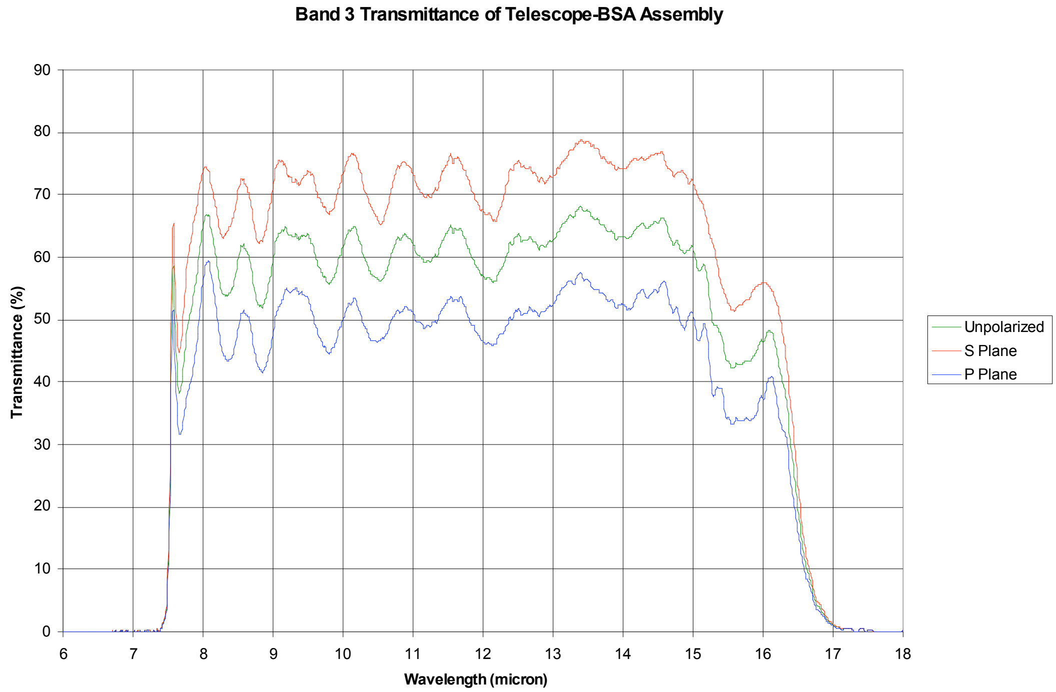

Figure 8: S and P polarization for the WISE optical system in band W3.

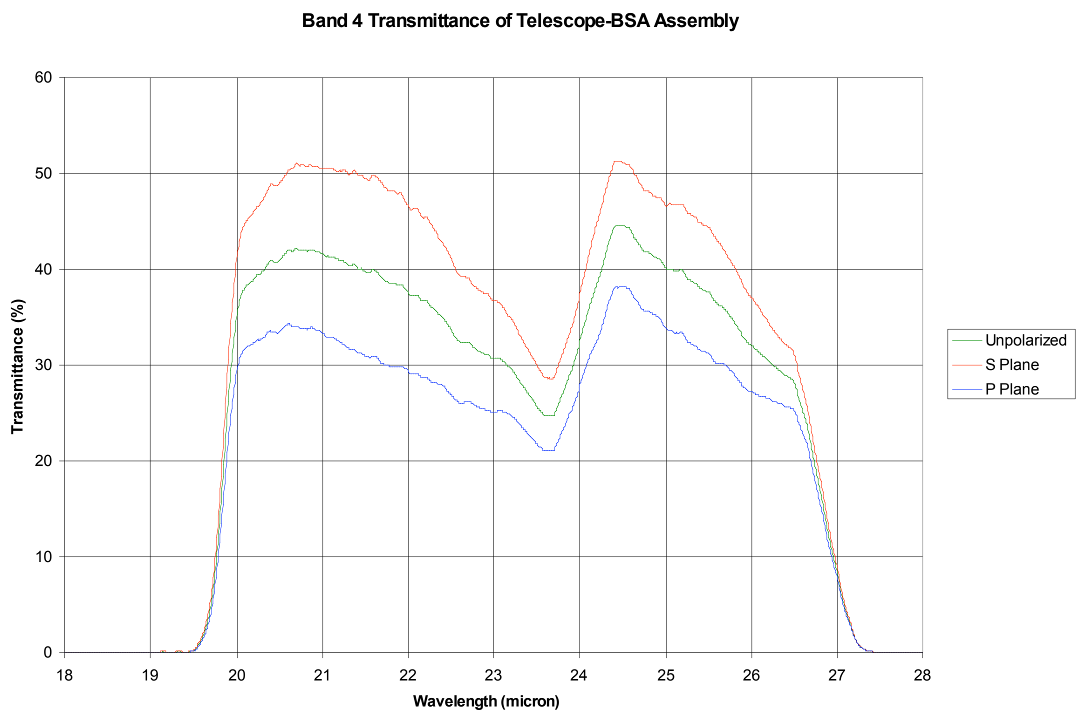

Figure 9: S and P polarization of the WISE optical system in band W4.

5.2.1.2 Bit Error Rate

The expected bit error rate is 1E-10, based on convolutional plus Reed-Solomon encoding. We calculate that this will lead to one undetected bit error in every 162 "frame sets." A frame set is one set of images in the 4 bands. Because Band 4 is 1/4 as big, it has a lower chance of error than the other 3 (0.25/3.25 or about 1 in 13, vs. 1/3.25) , so this means that for bands 1 - 3 we expect an undetected error in 1 out of about 500 frames, and 1 out of 2000 frames for band 4.

At SNR 20, one expects about 1500/700/150/15 sources per frame in bands 1/2/3/4 (Fazio et al. 2004, Popovich et al. 2004, Chary et al. 2004). With 14.5 noise pixels in band 1 this means about 20,000 pixels covered by SNR 20 sources (fewer in other bands), so the chance of an undetected bit error hitting an SNR 20 source is a few percent per frame. A few percent of 1/500 is < 1E-4, and at SNR 100 much less again, making this term negligibly small.
Note these errors are undetected, as detected errors are corrected. If we know there is an error, we will have to discard the entire frame, but we generally won't know. But even if we throw out 1/500 frames, the SNR drops from 100 to 100 sqrt(499/500) or 99.9, i.e. a hit of 1e-3.

5.2.1.3 Dark Current

WISE is required to produce 7% photometry on sources that are 100-sigma or brighter. We have allocated 2% of the photometric error budget to dark current instability. An unrecognized dark current will produce an error in the source photometry that may be better or worse than the requirement depending on the geometry of this unrecognized signal.
For relative photometry, we solve equation (11) above using P=0.02 and SNR=100. Table 8 below shows the maximum E_d we need to meet this requirement. We can see that this requirement is less stringent than the requirement on dark current stability derived from the need to keep sensitivity losses low.

Band	1	2	3	4*
Background (e-/sec/pix)	8	24	2200	1200
Read noise (e-/pix), assuming SUTR	19	19	55	55
Dark current (e-/sec/pix)	1	1	100	100
Noise pixels per source	10.3	14.05	37.6	28.1
Integration time (sec)	8.8	8.8	8.8	8.8
Number of frames	8	8	8	8
Required Ed from Equation (11) above (e-/sec/pix)	**4.8**	**5.5**	**35**	**27**

Table 7: Requirements on dark current stability Ed derived from photometric precision requirements. *Band 4 is binned such that every 2x2 pixels become one. Therefore the background and noise pixels are 4x higher than the actual value per unbinned pixel (listed here).

5.2.1.4 Flat Field Errors

5.2.1.4.1 Pre-Launch Flat Fielding

Flat fields for bands 3 and 4 can be well determined during IOC using normal WISE data collection. Bands 1 and 2 are more problematic because zodiacal background fluxes are lowest at these wavelengths and therefore many orbits of data will need to be utilized to form a master sky flat. Consequently, it is important to try to obtain a good set of flat fields for Bands 1 and 2 on the ground before launch.

5.2.1.4.1.1 Uniformity

The usual problems encountered with flat fields obtained prior to launch are (1) that the illumination is not in fact uniform and that the pupil is filled differently from when the sky background is used, and (2) the color of the illumination source is a poor match to the astronomical application. Every effort should be made to provide a uniform illumination source that over-fills the detector. Flat field frames should be obtained using the standard WISE exposure times, that is, by operating the detector as it will be operated in flight, but the total signal counts should be high enough to probe flat-field variations at the 0.1% level (>1 million collected photoelectrons).

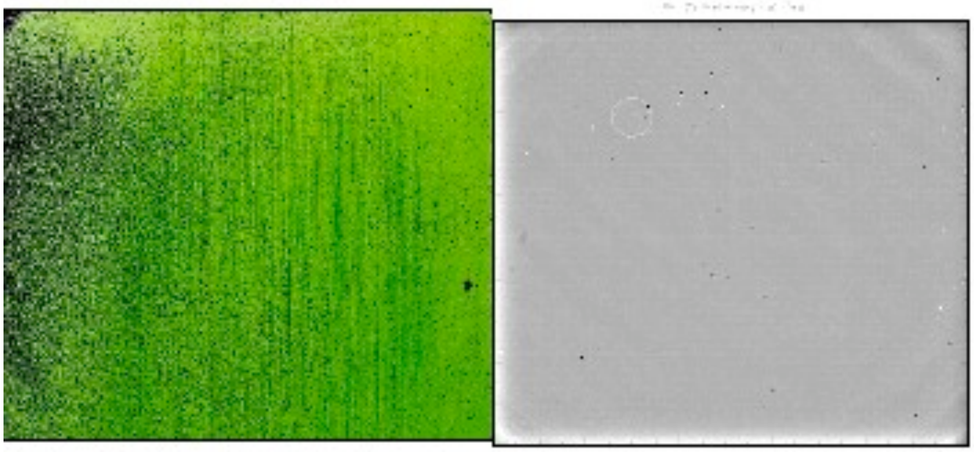

Figure 10: Illustrations of detector response. Left: HgCdTe array; right: Si:As array.

5.2.1.4.1.2 Flat field stability

Many frames should be obtained to investigate stability and repeatability. There is no magic number. Frames should be exposed to the same range of fluxes as expected from orbit. The impact of saturation on subsequent flat field frames should be measured. For Bands 1 and 2 where the in-orbit fluxes may be very low, good dark current subtraction and low noise performance will ultimately determine flat field accuracy and apparent stability.

5.2.1.4.2 On-Orbit Flat Fielding

The task is to remove the pixel-to-pixel variations in sensitivity and other non-uniform illumination effects by observations of a scene that is uniformly illuminated or a scene that change in the same way identically for every pixel. Typical response behavior of the WISE detectors is illustrated in Figure 10 using non-flight parts. Variations are large and must be corrected by flat-fielding, with a goal of achieving correction to at least 1% in all bands.

As there are no internal calibration sources on board WISE, the only practical approach is to use observations of the sky itself. Selecting regions of the sky with high backgrounds such as the zodiacal light, and using numerous scans to eliminate point sources by median filtering, can provide an adequate sky flat, albeit with the color of the zodiacal light. This method has been used extensively on Spitzer. Both IRAC and MIPS have created “superflats” using many combined sky observations and they have proven to be stable (IRAC User’s Manual; Reach et al., 2005, PASP, 117, 978). A limitation for WISE may be its wide field-of-view, and the resulting gradient in the zodiacal emission that will be observed in each frame.

There are two difficulties for WISE in using this approach. First, as shown in Figure 11, Band 1 at 3.3 microns is actually near a minimum in the sky background from all sources and secondly, the short on-chip exposure time and relatively high readout noise imply that Band 1 (and to a lesser extent Band 2) are read noise limited rather than background limited.

Table 8 shows the expected zodiacal background (MJy/sr) in each WISE band as a function of ecliptic latitude (beta) using DIRBE data from Ned Wright.

DIRBE	Band 3	4	5	6
WISE	Band 1	Band 2	Band 3	Band 4
Beta =	ecliptic	latitude		
0	1.65E-01	7.82E-01	3.23E+01	6.97E+01
30	1.04E-01	5.55E-01	1.89E+01	3.67E+01
60	7.28E-02	4.06E-01	1.27E+01	2.35E+01
90	6.51E-02	3.67E-01	1.12E+01	2.05E+01

Table 8: Zodiacal backgrounds in MJy/sr from DIRBE vs. ecliptic latitude.

In Table 9 these values are converted to detected photoelectrons per pixel in a single frame time of 8.8 s assuming efficiency factors for collecting area, optical transmission and QE. The derived conversion factors between MJy/sr and detected photoelectrons/s per pixel are 17, 21, 49 and 26 for Bands 1-4 respectively. A spreadsheet is available to enable input parameters to be changed easily. Clearly, in Bands 1 and 2 the number of detected photoelectrons is very small (on average) in a given WISE frame and the noise is dominated by readout noise (~15 e- CDS rms for the HgCdTe arrays).

Beta	Band 1	Band 2	Band 3	Band 4
0	2.47E+01	1.45E+02	1.08E+04	1.22E+04
30	1.55E+01	1.03E+02	6.32E+03	6.40E+03
60	1.09E+01	7.51E+01	4.23E+03	4.10E+03
90	9.71E+00	6.79E+01	3.74E+03	3.58E+03
Average	14.7	95.6	6028.6	6224.6

Table 9: Detected photoelectrons in a single 8.8s frame from zodiacal light per pixel.

Assuming the "average" values rather than the peak values in Table 9, and taking into account the read-noise dominated situation in Bands 1 and 2 then, Table 10 shows the expected photometric accuracy in the flat field from a single WISE frame at the average zodiacal light background level. Clearly, the zodiacal light is not a good flux source for efficiently flat-fielding Bands 1 and 2 for WISE. The reason why this works better for IRAC is that longer exposures (than 8.8s) can be used in Channels 1 and 2 to reduce the influence of readout noise.

Band 1	Band 2	Band 3	Band 4	Comment
118.55	20.51	1.53	1.50	single frame
5.18	0.90	0.07	0.07	single orbit
1.04	0.18	0.01	0.01	25 orbits

Table 10: Photometric accuracy for flat field correction (in %) using zodiacal light.

However, if all 523 frames obtained in a given orbit were combined to make a sky flat then the photometric accuracy would approach 5% in Band 1 and less than 1% in Bands 2, 3 and 4. By combining 25 orbits to form a "super sky" then the flat field errors would approach 1%, 0.2%, 0.01% and 0.01% respectively for Bands 1-4 This is consistent with the IRAC results in which sky flats obtained during the first two campaign years were combined to achieve similar flat field levels in IRAC Channels 1 and 2. We have allocated 3% photometric error due to flat fielding errors; hence, we have ample margin for this term for all four bands.

The bottom line is that there should be no problem flat-fielding the Band 3 and Band 4 detectors, with the caveat that little is known about their stability, but many orbits will be needed to get enough accuracy for Bands 1 and 2. Ground-based flat fields obtained prior to launch might provide additional useful data. The WISE frames need to be combined as if dithering was used (as with IRAC) in order to median filter point sources. As the background

changes significantly during one quarter of an orbit this may require some experimentation with code. Perhaps each frame needs to be normalized to its mean before being adding to the stack for the median, and perhaps of the 131 frames from ecliptic pole to ecliptic plane not all should be used, and perhaps it is best to use many batches and then find the median of medians.
However, we may be using the *change* in the zodiacal light for flat fielding because we don't have a shutter to give us darks. A similar method was employed successfully to construct nightly flat-field images for 2MASS, but changes in the twilight sky were observed rather than the zodiacal emission. For WISE image calibration, a selection of image frames that sample a wide range of zodiacal emission levels would be used, such as those taken during an ecliptic pole to equator scan. The relative response of each pixel to the changing mean illumination of each frame provides a measure of the relative gain, assuming that the illumination changes the same way for each pixel. Finally, we should consider whether or not it would it be helpful to simulate some of the possible reduction algorithms using IRAC frames. Apart from the option to observe the dust cover prior to ejection, it would seem that no special IOC actions are needed to prepare for this calibration method.

5.2.1.5 Detector Sub-Pixel Response Variations

Gaps between pixels and variations in the doping levels across a pixel are two of the possible ways to have gain variation across a single pixel that can result in an increase in photometric dispersion. However, WISE's images are at least critically sampled in all four bands so the expected photometric error from this effect is expected to be relatively small. Photometric residuals as a function of sub-pixel source position will be characterized using on-orbit measurements, as they were for 2MASS.

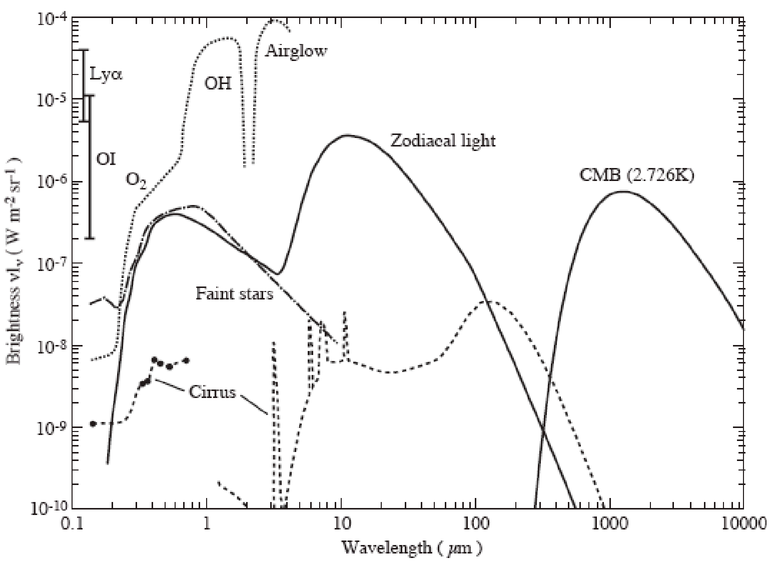

Figure 11: The diffuse night sky brightness from Leinert et al. (1998).

5.2.1.6 Residual Non-Linearity

This section highlights pre- and post-launch activities needed to measure/characterize non-linearity and to check that saturation is being adequately flagged by the software.

5.2.1.6.1 Linearity

For brighter sources, electronic arrays exhibit non-linear behavior in count rates measured as a function of exposure time, and this non-linearity can appear long before saturation or full well is reached. We need to characterize non-linear behavior both prior to and after launch for each of the four arrays. We allocate no more than 2% due to residual linearity effects in the overall photometric error budget.

a. In the lab: All samples of the *N* samples up the ramp will be saved. Testers will flood the array with a steadily illuminated source, then repeat the experiment with illuminations covering a wide range of brightnesses. (This is accomplished by a suite of apertures of different sizes – ranging from ~20 to 7000 microns – that allow varying levels of non-focused light through.) There is not a mechanism to repeat this experiment with focused point sources, so that will have to be done during IOC. Note that we should also perform a lab test to make sure the changing of coefficients (see text below) works as expected.

b. On orbit: During survey operations, WISE will not save each of the N (1 through 8) samples up the ramp but instead will report only a sum, d, of the form $d = 128 + \Sigma^{N}_{n=1} c_n p_n$, where n is the sample number, c is a multiplicative coefficient, and p is the count level in that pixel. There are two methods for obtaining linearity; one involves using the stim sources to flood illuminate the arrays in all four bands (Method 1), and one involves using on-sky measurements taken while scanning (Method 2). In both cases, we need to upload a new set of c values after a set of several exposures in order to vary the effective integration time.

c. Our current baseline is to use the stim sources only; the second method is considered a backup plan. The advantage of Method 1 is that it allows us to measure the linearity of each pixel in all four arrays. The flux of the stim source can be adjusted from zero to saturating. Although the illumination pattern will not be uniform, it will fill the entire array. In Method 1, we can perform linearity measurements of bands W1 and W2 prior to cover ejection. We should take at least three images with each coefficient setting to verify that the command to switch coefficients has been correctly implemented. We can collect stim source images of W3 and W4 prior to scan mirror synchronization. This method requires much less time on board the spacecraft, and the time that it does require is prior to scan mirror synchronization. For Method 1, we require three images taken at each coefficient setting, and there are nine coefficient settings that we require. This translates to approximately five minutes' worth of data for W1 and W2 and another five minutes' worth of data for W3 and W4.

d. The advantage of Method 2 is that it allows us to measure the linearity of individual sources. However, it has the disadvantage that it does not uniformly sample all pixels, only those that happen to have sources on them. Also, it takes significantly longer on board the spacecraft, and it must occur after scan mirror synchronization. For Method 2, we propose to allocate eight consecutive orbits to this experiment, uploading a new set of c values for each orbit so that counts only up to sample $n = orbit\ number$ are saved for each. (This is the same as changing the total exposure time for each orbit.) By tweaking the WISE flight plan so that there is no cross-stepping between these orbits, we will be able to observe the same set of stars at all eight integration times.

Time needed in IOC: Eight orbits of data are required. The orbit with the fewest observed stars will occur when WISE scanning passes through the NGP and SGP. Curiously, this occurs roughly seven weeks after an early-Nov launch and thus is close in time to IOC activities. We will use this as the worst case since it will have the fewest out-of-plane stars. Using 2MASS star counts as a guide, we predict that this single WISE orbit (assuming the 8-consecutive orbits are not perfectly co-aligned and suffer 20% loss of overlap) will contain 256,000 stars with $|b|>10^{O}$ and $Ks<13.5$ mag, which corresponds roughly to W1 SNR>50 (using a mean value of $W1\text{-}Ks\sim0.2$ mag for stars of these brightnesses, a W1 flux at zero mag of 280.9 Jy, and a 5σ W1 sensitivity of 120 μJy.). For W4, this same SNR>50 limit corresponds to ~26 mJy. Based on the SWIRE counts in the MIPS 24um channel, we should expect ~450 high-latitude W4 point sources with SNR>50 in our WISE 8-orbit coverage; these numbers will increase dramatically in the portions of the orbit crossing the galactic plane. Based on these predictions, we believe that the number of brighter stars we'll observe in the 8-orbit experiment provides sufficient statistics for characterizing linearity.

Dependencies on other activities: Normal survey flats can be used for flat fielding. However, darks at each of the eight different integration times should be obtained for calibration purposes. In-lab darks taken in normal sample-up-the-ramp mode can be used for this; W1 and W2 darks at all eight integration times should perhaps also be obtained on orbit and included in the IOC plan. We require survey-like (round) images, so these activities should take place after scan synchronization. Otherwise, it would be ideal to acquire these data early in IOC so that results of analysis can be fed back into the WSDC processing pipeline.

Software needed: Data can be processed with the normal WSDC pipeline using only namelist changes to account for non-standard dark frames, exposure times, etc. Analysis software will need to be written to estimate the non-linearity calibration factors. This will use a method to optimally combine all the photometric measurements across all SUR exposures.

5.2.1.6.2 Saturation

According to Mark Larsen (SDL), the A/D converters will saturate (~100,000 electrons) before full well (~150,000 electrons) is reached. In principle, we can search for a max value ($\sim 2^{15}$ = 32768) as the trigger for saturation. However, the payload electronics will fill pixel values with special reserved numbers of 32752+*n*, where *n* is the sample-up-the-ramp number at which saturation is first reached.

e. In the lab: During linearity tests, run the illumination high enough so that the A/D trigger is encountered. As illumination continues to increase, check that the special value flags kick in and change as expected.
f. On orbit: Verify that saturated flag values are being reported for some sources. This can be done in two stages. (1) W3 and W4 should both saturate when the cover is still on, so a simple check of cover-on data in these bands will show whether saturation is being correctly flagged. (2) Once the cover is off, check that pixel values in all four bands are being reported as expected, using a set of stars expected to be saturated (modulo errors in their photometry estimates).

Time needed in IOC: No extra time is needed for this experiment, as data from other IOC tasks (e.g., the linearity checks above and any data acquired during cover-on activities) can be used for the same purpose.

Dependencies on other activities: None. The on-sky checks can be made on any patch of sky once normal survey scanning has begun.

Software needed: Code will be needed to identify stars, using 2MASS/USNO-A/Spitzer photometry, that are likely to be near or above saturation in each of the four WISE bands.

5.2.2 Measurement & Sky Errors

5.2.2.1 Source and Sky Annulus Noise

Assume an SNR=100 source. The photon noise from such a source will contribute 1% to the photometric error.

We then seek to keep the photometric error resulting from the measurement of the background in the sky annulus to a small fraction of the source error, say 0.1%. This can be accomplished by using a large enough number of pixels in the sky annulus. For band 1, where the background is very low (only 14.7 e-/sec from Table 9), the total background signal in 8.8 sec is 129 e-. With a CDS read noise of 15 e- and a dark current of 5 e-/sec, the total error in the background measurement is ~19 e- per pixel, so with a single pixel, we will measure a background of 129 ± 19 e-, or 7% photometric error. To reduce this photometric error to the desired level of 0.1%, we require (7/.1)^2 = 4900 pixels. This is equivalent to a radius of ~40 pixels for band 1. For band 3, the background is very high, 6029 e-/sec from Table 9, and the read noise is 70 e- CDS; dark current is 100 e-/sec, so we are background-dominated. In this case, the background on a single pixel is so high that the signal-to-noise ratio of the background is sqrt((6029+100 e-/sec)*8.8sec + 70^2 e-) = 239, or 0.45%, so we only need (0.45/.1)^2 = 20 pixels to reduce the background photometric error to a negligible 0.1%. However, this must be balanced against the need to minimize the background apertures to reduce the error contributed by flat fielding residuals and background variations due to real astrophysical structure.

5.2.2.2 Crosstalk

Crosstalk will affect point source photometry by causing the flux from the source to “bleed” into neighboring pixels. The requirements on electrical crosstalk have been flowed down from the WISE Payload Requirements Document. The effects of crosstalk have been accounted for in the estimates of the image quality in each of the four bands; see doc TBR (Image Quality Report).

5.2.2.3 Cosmic Rays

The WISE radiation environment is specified in the Facility Requirements Document. Based on these requirements, we expect ~30-50 cosmic ray hits per frame. A source hit with a cosmic ray will have to have that frame thrown out of the coadded image, resulting in a loss of photometric precision due to decreased effective integration time. If the average number of frames per source is eight, dropping one frame will result in an increase in photometric error of ~14%. However, very few sources will be hit with cosmic rays. At SNR 20, one expects about 1500/700/150/15 sources per frame in bands 1/2/3/4. With 14.5 noise pixels in band 1 this means about 20,000 pixels covered by SNR 20 sources (fewer in other bands), so the chance of a source being hit by a cosmic ray is ~0.2%, so the average loss of photometric accuracy to the catalog from cosmic rays is only 0.03%. We have allocated 0.1% to this term.

5.2.2.4 Latent Images

We plan to build a model of latent images in our detectors arrays, both Si:As and HgCdTe, that is similar to the treatment used in 2MASS data processing. In our experience with the 2MASS HgCdTe and Spitzer MIPS Si:As arrays, it is possible to have both bright and dark latents with maximum amplitudes of ~1% or less of the original source. We were able to model their amplitudes to 10-40% accuracy. We will use our models of latent behaviors to flag and possibly remove sources from the catalog which are coincident with the predicted position of latent artifacts in any of their exposures. Latent image artifacts will not be corrected in the WISE Atlas Images. Thus, the only potential impacts to photometric error from latent images are from unrecognized latents, which could result from imperfections in our latent behavior models.

Let us then assume that we have a latent image produced by a bright source, but we do not recognize it as a latent since we have a 40% error on our models of latent amplitudes as a function of time. If the latent amplitude is 1%±0.4% amplitude, it could produce at most a 0.4% photometric error in the source photometry. Hence, we have allocated 0.5% photometric error to unrecognized latents. We will be making ground-based measurements of latent image properties at SDL on the flight arrays, along with measurements of how well annealing removes them. We are also performing testing on latents on a non-flight Si:As array at NASA Ames. Annealing is not possible for the HgCdTe arrays.

5.2.2.5 Illumination Level Estimation Errors

In order to measure the flux of a point source, we must be able to subtract out its background, which includes the astrophysical background (e.g. zodiacal light), any stray light, ghosts, glow from the telescope, interference fringes from the filters, etc.

The dominant source of stray light for WISE is likely to be from the Moon. We have placed a requirement on the system stating that we must be able to collect data without increasing the noise in all four bands by more than 10% as close as 15° from the Moon (see design memo SDL05-967 Stray Light Requirements Analysis). This has created a requirement on the maximum stray light allowable by the system: the normalized detector irradiance in band 1 must be <1e-5 at 15° from the Moon. If the noise increases by 10%, then photometric accuracy is degraded by 10%; however, WISE will only point this close to the Moon 1% of the time, so the end result will be to degrade the photometric accuracy of the entire catalog by no more than 0.1%.

We will make a map of ghosting and other types of stray light at SDL with the MIC2 chamber as described in the SDL Payload Electro-Optical Characterization Plan. This model will be updated on-orbit.

The WISE telescope will be cooled to 17K; at this temperature, there is essentially no background due to the telescope structure at any of the four WISE bands.

Table 9 gives the average astrophysical backgrounds for the four WISE bands, and Table 10 gives the number of orbits it takes to reduce the measurement errors. We plan to combine enough frames to reduce the error in the measurement of the astrophysical background to <1% per Table 10.

Stray light due to thermal emission from the aperture shade was estimated for WISE band 4 in the SDL memo SDL/07-062. It is estimated that the 110 K shade will produce a background current of ~15 e-/sec per unbinned pixel in band 4, which is negligible compared to the zodiacal background (see Table 9).

5.2.2.6 Confusion Noise

The 5-σ confusion noise for all four bands is given in Table 1, along with the required sensitivities for a 5-σ source. We can estimate the photometric error due to confusion noise by computing the ratio of the confusion noise to the flux of a 100-σ source (which is 2.4, 3.2, 13, and 52 mJy for bands 1-4, respectively). Confusion results in a photometric error of 0.52%, 0.38%, 0.52%, and 0.36% for bands 1 – 4, respectively.

5.2.2.7 Aperture Correction Errors

An aperture correction is the difference between the measured flux in a source aperture of finite radius compared to the actual source flux, which is equivalent to the flux measured with an infinitely large aperture radius. Enlarging the aperture radius necessarily increases the noise due to the background, and makes the measurement more susceptible to flat fielding, dark subtraction, and sky subtraction errors. Also, variations in the PSF across the field, confusion noise, and proximity to nearby sources can produce errors in the aperture correction measurement. We can make an estimate of the aperture correction using the assumption that we use stars that are much brighter than the background level, and we assume that flat fielding errors are small in the objects' vicinity, i.e. <0.1%.

Definitions:
Area of the larger of two apertures that encompasses most of the flux of an isolated calibration star = A_1
Area of the nominal measurement aperture = A_2
Background-subtracted source flux in aperture A_1 / background-subtracted source flux in aperture A_2 = A_C = S_{A1} / S_{A2}
The fractional error in A_C = E_{AC}
Then we can estimate E_{AC} as

$$(16)\quad \frac{E_{AC}}{A_C} = \sqrt{\left(\frac{E(S_{A1})}{S_{A1}}\right)^2 + \left(\frac{E(S_{A2})}{S_{A2}}\right)^2} = \sqrt{\left(\left(\frac{1}{SNR_{A1}{}^2}\right) + \left(\frac{1}{SNR_{A2}{}^2}\right)\right)}$$

If A_1 and A_2 are placed on a bright calibration star, assuming that SNR_{A2} >=100, then SNR_{A1} will be larger than 100 if the noise is source-photon noise dominated since $A_1 > A_2$. Thus, we expect

$$(17)\quad \frac{E_{AC}}{A_C} \le \sqrt{\left(\frac{1}{100^2} + \frac{1}{100^2}\right)} \le \sqrt{2}\% \le 0.014 = 1.4\%$$. We have allocated 1.5% for this error.

5.2.3 Photometric Zero Point Errors

5.2.3.1 Predicted Standard Star Absolute Fluxes

In order to derive a photometric zero point, we must know the predicted in-band flux densities of the WISE calibration standards. These fiducial sources include both stellar and non-stellar sources such as ULIRGs. The end-to-end relative spectral response curves (RSRs) are measured on the ground at SDL and incorporate all knowledge of the transmittance and reflectance of every optical component in the instrument, including the detector response. To predict the WISE irradiances of our standard stars we develop spectral energy distributions from UV/optical to the mid-infrared of two categories of star: A0-5 dwarfs and K0-M0 giants.

The intrinsic spectral templates for these A stars are represented by Kurucz synthetic photospheric spectra based on grids of model atmospheres. The cool giant spectra, by contrast, are not based on models. Each giant is constructed using the observed archetype of a unreddened star of the same spectral type as a template. The reddening of the individual star to be templated is applied to the archetype's spectrum then the reddened template is normalized absolutely using optical and infrared photometry independently calibrated, consistently with the spectra.

The in-band flux of a star in any WISE band is the integral of the appropriately reddened A-type stellar photosphere or K-MIII template over the associated RSR. Division of the in-band flux by the wavelength or frequency bandwidth yields the isophotal monochromatic flux density (in W/cm^2/μm or Jy). The methods are fully described by Cohen et al. (1999, 2003) and the results have been absolutely validated by MSX (Price et al. 2004).

Quantitative uncertainties quantitatively are assessed from knowledge of each standard's spectral type, reddening, the wavelength-dependent errors in the interstellar extinction curve, the shape of the continuum and absorption features of the archetype or Kurucz photospheric spectrum, the errors in the ensemble of measured photometry of the standard used to normalize its spectral shape. The WISE flux and magnitude system will be traceable absolutely to MSX and consistent with the Spitzer system.

Our experience of developing the suite of absolute calibrators for IRAC (Cohen et al. 2003; Reach et al. 2005) demonstrates that absolute in-band fluxes of standards created by this technique have uncertainties of 2% for most bands. Each fiducial star provides an estimate of the conversion between ADU or DN and absolute physical units. For a small set of A-type IRAC standards, the overall absolute uncertainty including all relevant errors is 2.0% (Reach et al. 2005). We believe that we can achieve an ensemble-averaged error for the calibration of WISE that is significantly smaller than 2% by leveraging WISE photometry of the many Spitzer standards established for routine instrumental calibration and purpose-built for Legacy projects, and by developing secondary WISE standards too.

5.2.3.2 Color Term Knowledge and Stability

This term refers to our ability to effectively monitor the system RSRs over the lifetime of the mission. The RSRs are characterized on the ground; however, darkening of the filters due to radiation and changes in detector quantum efficiency could occur. We will quantify changes to these RSRs in orbit by comparing the relative colors (ratios of in-band fluxes) of an ensemble of red and blue standards as a function of time. These calibration measurements will be based upon measurements of the generally blue primary stellar calibrators that WISE will see multiple times per day at the ecliptic poles and of less frequently encountered red calibrators, allowing us to recognize color changes that indirectly trace time variations in the RSRs. We plan to use enough red and blue standards at the beginning and end of the mission to allow us to monitor the RSR stability to within 2%.

5.3 Absolute Photometric Error

WISE does not have a requirement on absolute photometric precision. However, this section contains a best-effort estimate of the anticipated absolute photometric error for all four bands. This section presents the methods by which WISE photometry will be placed on the same magnitude system as that defined by MSX and echoed by Spitzer.

The primary approach is to measure a set of pre-defined standard stars in each of the WISE NEP and SEP single fields of view (hereafter the WISE CVZs: constant viewing zones). These fiduciaries are themselves Spitzer IRAC standards measured during Spitzer's IOC. Some are used as IRAC primary calibrators in the NEP. Our current goal is to establish a similar set in the WISE SEP CVZ. This will be accomplished by observations to be made with all three of Spitzer's instruments if the WISE team's Spitzer Director's Discretionary Time proposal is successful.

We have selected 10 known Spitzer standard stars in the northern WISE CVZ and, using our proposed photometric surveys at the SEP, we plan to isolate 10 potential calibrators in the WISE southern CVZ. By providing absolute calibrators at the two ecliptic poles we hope to define frequent zero points for WISE photometry of bands W1, W2, and W3, although the latter will be based on fewer standards at the poles than are available for W1 and W2. Having calibrators at both poles offers robustness of these calibration zero points when we miss one or other pole on an orbit in which a momentum dump, an anneal, or a downlink is scheduled.

No W4 calibrators are known in the CVZs. If we are unable to develop any in either WISE CVZ then we will rely wholly on a distributed network of W4 standards drawn from stars without debris disks observed in the Spitzer FEPS Legacy program, and on standards within the Spitzer CVZs. We need to exploit other alternatives across the sky so that W4 zero points are not separated by long periods of time. A distributed network of WISE calibrators is definitely an option in the 3 shorter wavelength WISE bands. These will be derived from the roughly 1100 calibrators built as calibrators for IRAC and MIPS to support several Legacy programs. The objective of such widely dispersed sets of standards is again to ensure an acceptable cadence of zero point determinations, albeit less frequent than once or twice for every orbit. Most promising so far is the set of 238 calibrators created to support the SAGE

LMC legacy which includes the SEP. These stars surround the SEP and preliminary simulations of WISE operations suggest that one might see as many as 3 of these stars on every WISE orbit. How many will prove to be valuable calibrators in any of the four WISE bands may not be estimated until the WISE relative spectral response curves are measured end-to-end or until we can assess true detection thresholds and saturation levels for each band when the instrument is on-orbit.

5.4 Astrometric Error

The Level 1 requirement states that the WISE catalog shall have root mean square position error <0.5" with respect to 2MASS for SNR > 20 (<1.0" for the minimum mission); see Table 2. The basic process by which WISE astrometry will be performed is described in Section 3.1.2. The final astrometric solution will be computed using a combination of all four WISE bands whenever possible; the majority of sources will have flux detected in more than one band. Figure 12 depicts the typical astrometric errors from the 2MASS survey; errors in the range of 0.06-0.07 arcsec are typical for sources brighter than ~20-σ. Figure 13 shows our rms astrometric error budget for the catalog. The astrometric error budget consists of two primary types of errors; those that derive from the instrumental calibration, and those that derive from source measurements.

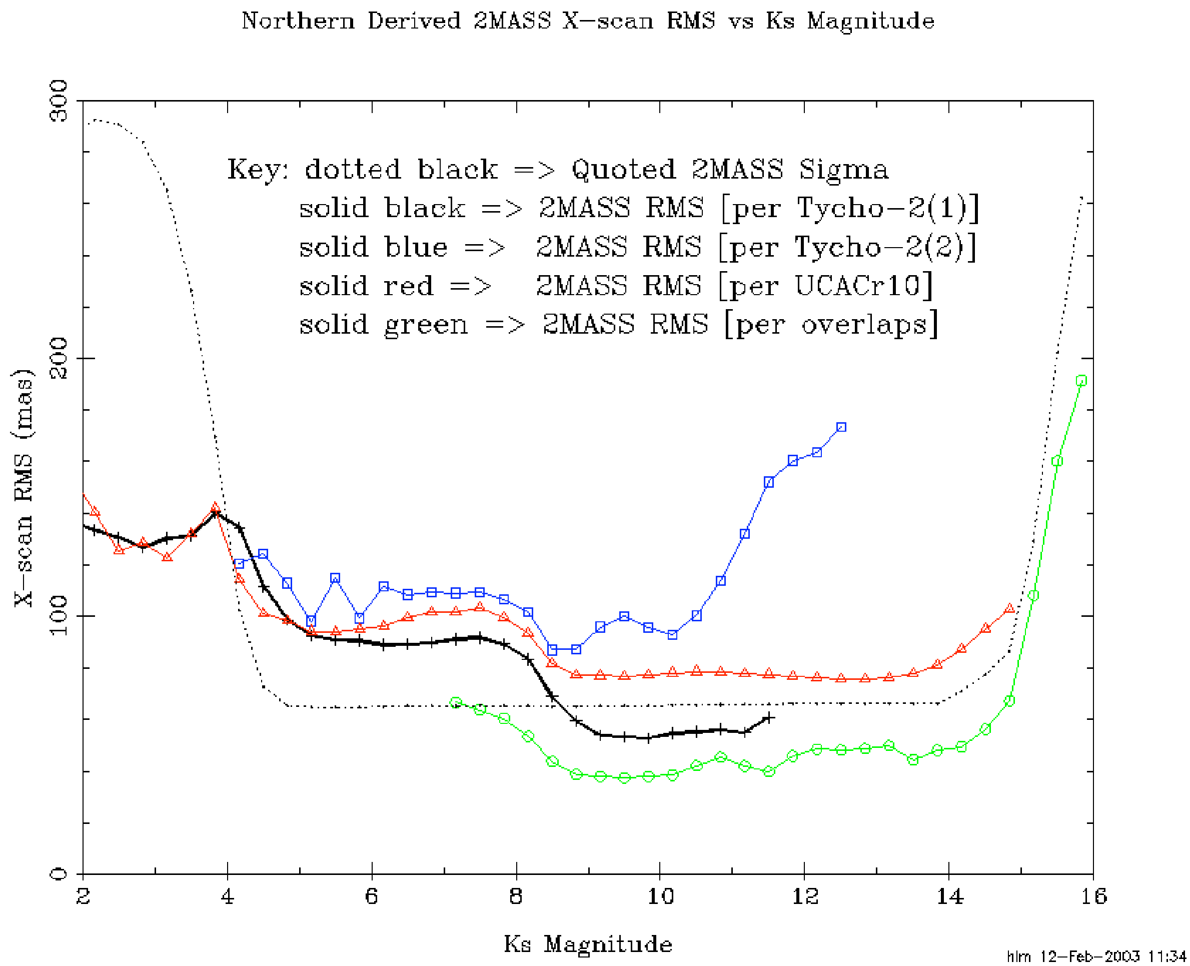

Figure 12: The astrometric performance of the 2MASS survey as a function of source magnitude.

Band 1 Astrometry 1-σ	0.407	arcsec

Instrument Calibration Errors	0.101	
Band to band registration errors	0.010	
Boresight knowledge error	0.010	
Distortion correction error	0.100	A, T

Measurement & Sky Errors	0.394	
Centroiding error (for SNR =20 source)	0.350	D
Cosmic ray-induced noise - source & sky	0.01	A
Latents (short and long term)	0.01	T
Stray Light (in source)	0.002	A, T
Background level estimation errors (flat fielding, stray light, transients, etc.)	0.003	A
Confusion noise	0.18	A

Figure 13: Astrometric error budget for band 1.

5.4.1 Instrumental Calibration Errors

5.4.1.1 Distortion Correction Error

We must have a map of distortion across each WISE field of in order to map the transformation from pixel to J2000 equatorial coordinates. Distortion will be measured at SDL in the MIC2 chamber using a 7x7 grid of locations across the focal plane array with the scan mirror set at the middle and both ends of its range (see section 5.4 of the SDL Payload Electro-Optical Characterization Plan). The distortion is found from the difference between the observed position and the expected position of the point source based on the designed focal length, pixel pitch, and position of the MIC2 mirror. We assume that we will be able to generate an extremely bright (SNR>100) image using the MIC2 collimator. If the band 1 image size is expected to be ~10.5 noise pixels when in this configuration in MIC2 (i.e. no spacecraft contributions present), then we expect to be able to compute the image centroid to ~0.1 arcsec at each location in the grid; this would be the worst-case error in our distortion map. At SNR 20, one expects about 1500/700/150/15 sources per frame in bands 1/2/3/4. On orbit, we will refine our distortion map by using the 2MASS sources in each frame as references.

5.4.1.2 Band to Band Offset Errors

WISE views the same area of the sky simultaneously in all four bands by using three beamsplitters. We will measure the registration between the four bands at SDL using the MIC2 chamber as a starting point. The band to band registration will be updated on orbit using the ensemble of all sources in each frame. For band 1, if the error on an individual source's centroid is ~0.35 arcsec, then the error will be reduced to ~0.01 when we combine the 1500 sources in one frame. Since the telescope and imager should be in an extremely stable thermal environment, it is unlikely that the band

5.4.1.3 Boresight Knowledge Errors

The ADCS-boresight calibration task consists of measuring the angular offset between the pointing position that is reported by the spacecraft's ADCS (attitude determination and control system) and the true boresight position of the focal plane. The spacecraft will use the input of its star trackers and their internal star catalogs, plus the telescope alignment offset measurement during ground test to report a position associated with each image frame. That position will likely be offset slightly from the very accurate focal plane center position that we are able to reconstruct using the reference stars in each image frame.

The goal during IOC will be to measure the difference between where the ADCS thinks we are pointing and the actual measured position. We will get a good measurement of the offset from the very first on-orbit scanning data because each image frame will be reconstructed in the 2MASS reference system. Converting from the mean central position of each array to equatorial coordinates will then be straightforward.

No special on-orbit observations are expected to be needed; the solution will come out of the standard frame astrometric solutions in the data processing pipeline. However, we will need observations at the extremes of solar elongation angles to check for thermal effects as in IRAS.

We will need the telescope alignment offset from ground testing, including at a minimum the band-to-band offsets, rotations, focus, and scales. The end-to-end system alignment plan is described in the WISE Alignment Plan (JPL/34391). Measured distortions derived from software modeling of the optical prescription will be needed, and if possible, distortions measured from ground tests also. Since the beamsplitters are opaque at the measurement wavelengths, the registration of the four detectors will be measured with respect to fiducials on the beamsplitters, which will in turn be referenced to an alignment cube on the cryostat flange. This will be measured with respect to alignment cubes on the spacecraft deck and the star trackers.

We estimate that the pre-launch ADCS-to-telescope boresight knowledge should be 0.5°. This may depend on how much distortion there is and how densely populated the image fields will be with 2MASS reference stars. With an initial uncertainty of 0.5°, it will not take too long to search that area to perform the pattern matching necessary to lower the error in the ADCS-to-telescope boresight offset significantly.

The star trackers and their pointing data will be required on-orbit. Image frame data from the normal data reduction pipeline will be used for the final boresight determination by identifying sources in the 2MASS astrometric star catalog and modeling the astrometric mapping of the sky onto the focal plane.

We will need the software to provide the attitude of the spacecraft at the times of the starts of mirror scans. WISE source detections will be positionally correlated with 2MASS PSC sources as part of the standard data reduction process at the WSDC. The astrometric solution will include the rotation matrix (or quaternion) to relate spacecraft coordinates to the instrument boresight. We estimate that we can reduce the boresight knowledge error to 0.01 arcsec in band 1.

5.4.2 Measurement & Sky Errors

5.4.2.1 Source Centroiding Error

We can approximate the centroiding error of a single source as the FWHM divided by the signal to noise ratio. If we approximate the PSF as a Gaussian, the relationship between the FWHM and the number of noise pixels, N_p, is given by

$N_p = 2.226\ FWHM^2$

For band W1, $N_p = 14.5$, so the FWHM is ~7 arcsec, so the centroiding error per $20-\sigma$ source is 0.35. The centroiding error in band 4 can be driven down to less than the required 0.5

arcsec for many objects by band merging with the more numerous and accurate band 1 sources.

5.4.2.2 Latent Images

As described in section 5.2.2.4., we will flag sources that are known to have latent images superimposed on them. Therefore, the primary error we need be concerned with due to latents is that due to biases induced by unrecognized latents. In band 1, the astrometric solution will be derived from the 1500 sources that appear on average in each frame. It is unlikely that a significant number of these sources will be corrupted by unrecognized latents, although this is difficult to quantify at present. Therefore, we will assign 0.01 arcsec astrometric error due to unrecognized latents.

5.4.2.3 Confusion Noise

For band 1, the flux of an SNR=20 source is 0.48 mJy. From Table 2, the 5-σ confusion noise is expected to by 0.063 mJy; therefore, the 1-σ level is 0.013 mJy. In band W1, the FWHM is ~7 arcsec, so we should use a measurement aperture radius of 2.5 pixels. If we use a measurement aperture with a radius of 2.5 pixels, the most such a confused source could distort the centroid of a single image would be given by the center of mass equation (TBR),

$$R = \frac{1}{M}\sum m_i r_i$$

which for band 1 works out to be (0*0.48 + 0.013*2.5 pixels*2.75 arcsec/pixel)/(0.48 + 0.013) = 0.18 arcsec for a single source.

In band 4, the flux of a 20-s source is 13 mJy and the 5-σ confusion is noise is 0.95 mJy from Table 2. If we use a measurement aperture radius of six pixels, then a confused source could distort the centroid of a single image by ~0.48 arcsec. However, since most W4 sources will have a band 1 counterpart, the effects of confusion will be lower than this in most cases.

5.4.2.4 Stray Light in Source

The dominant source of stray light should be from the Moon, which should look like an increase in the background level with relatively little spatial structure. We have required that the stray light suppression be sufficient to limit the increase in noise in band 1 to no more than 10%. This would increase astrometric error by ~0.002 arcsec on average (since we have 1500 sources on average per frame in band 1). WISE observes within 15° of the Moon ~1% of the time, so the rms increase in astrometric error should be negligible for the whole catalog. Sources which are known to have been affected by ghosts, glints, or diffraction spikes will be excluded from the astrometric solution.

5.4.2.5 Fractional Pixel Approximation

Since WISE is critically sampled in all four bands, we assume the astrometric error due to fractional pixel approximations is negligible.

5.4.2.6 Cosmic Rays

Since we expect only 0.2% of sources in the catalog to have been contaminated by cosmic rays (see section 5.2.2.3) in band 1, we estimate that the astrometric error contributed by cosmic rays will be ~0.01 arcsec.

6 References

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