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Pre-Launch characterization of the WISE payload

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ABSTRACT

The Wide-field Infrared Survey Explorer (WISE), launched in December 2009, is a NASA-funded Explorer mission that is providing an all-sky survey in the mid-infrared with far greater sensitivity and resolution than any previous IR survey mission. The Utah State University Space Dynamics Laboratory designed, fabricated, and characterized the science payload, which is a cryogenically cooled infrared telescope with four 1024x1024 infrared focal plane arrays covering from 2.8 to 26 μm . Pre-launch characterization included measuring focus, image quality, repeatability, response non-linearity, saturation, latency, absolute response, flatfield, point response function, scanner linearity, and relative spectral response. This paper provides a brief overview of the payload, discusses pre-launch characterization methods, and presents key performance results from ground characterization and early on-orbit performance.

Keywords: WISE, all-sky survey, infrared satellite, infrared instrument, solid-hydrogen, HgCdTe, Si:As, instrument characterization

1. INTRODUCTION

The Wide-field Infrared Survey Explorer (WISE)¹ is a NASA mission to survey the entire sky in four infrared bands at 2.8-3.8 μm , 4.1-5.2 μm , 7.5-16.5 μm , and 20-25 μm (referred to as bands 1 to 4 in this order). Images are collected by 4 1024x1024 pixel focal planes. Two HgCdTe arrays operating at 32 K cover bands 1 and 2, and two Si:As arrays operating at 7 K cover bands 3 and 4. Cooling for the focal planes and optics are provided by solid hydrogen cryostats, one cools the optics and HgCdTe detectors, the other cools the Si:As detectors. The tanks are filled prior to launch by flowing hydrogen gas into the tanks and flowing liquid helium through cooling loops to freeze it. These cooling loops are also used to cool the instrument for ground testing. The optics consist of a 40-cm afocal telescope with 8x magnification followed by a scan mirror, imaging optics, a beamsplitter assembly and the detectors. Figure 1 shows the WISE payload.

Figure 1: Exploded view of the WISE Payload. The largest piece is the cryostat, and the middle piece is the telescope, scan mirror and imaging optics with the beam splitter assembly shown separate to the right.

WISE is in a 525-km sun synchronous orbit with the telescope continuously pointing to zenith. Images are collected every 11 seconds with the scan mirror used to freeze the motion of the sky during integration. Over one orbit, the instrument observes a circular strip of sky. This strip moves slightly by the next orbit and thus WISE covers the full sky in 6 months. WISE launched on December 14th, 2009, and the mapping mission began in mid-January after a month of instrument checkout and calibration. The solid hydrogen is currently expected to last until early November, which will allow for 1½ full sky maps.

To verify instrument performance and to assist with calibration on-orbit, WISE required extensive ground characterization. This paper discusses the overall characterization testing and selected test results.

2. CHARACTERIZATION TESTING OVERVIEW

The significant items that were characterized on the ground are:

- 1) Focus (focus was measured and the instrument adjusted until it was in focus)
- 2) Image Quality
- 3) Dark offset level
- 4) Dark level variation and gain variation
- 5) Detector non-linearity
- 6) Flatfield
- 7) Relative Spectral Response (the response to incident power as a function of wavelength for each band, including both response in and out of the spectral band)
- 8) Absolute Response
- 9) Optical distortion
- 10) Saturation level
- 11) Latent images
- 12) Droop
- 13) Scan mirror motion linearity

Most of these characterization tests were performed effectively with the Space Dynamics Lab's Multi-function Infrared Calibrator #2 (MIC2). MIC2 is a vacuum chamber that can operate at liquid helium temperatures containing several types of calibration sources that can be interchangeably presented to an instrument under test without breaking vacuum. The instrument (or a vacuum chamber containing the instrument) is attached to the MIC2 exit port and normally shares the vacuum with MIC2.

Figure 2: The MIC 2 source configurations. Configurations are changed by movable optical elements.

Figure 2 shows the MIC2 configurations available. The first configuration is the extended source, which is a blackbody with a temperature range of ~ 20 to ~ 320 K. The next configuration is a collimator consisting of a 200" focal length collimator and a set of precision apertures on a slide. The actual source for the collimator is external to MIC, outside an entrance port with a window. For WISE this window was KBr, which passes all of the WISE spectral range with some fall-off at the long end of band 4. External sources used with WISE were small blackbodies with a 200 to 1200 C temperature range, radiation from the room, and a Fourier-Transform spectrometer for the relative spectral response tests. Between the entrance window and the apertures is a set of cold spectral filters on a slide, which are used to help measure out-of-band spectral response by blocking transmission in the instrument passband(s). The third configuration is a scatter source, which scatters power from an external source so that only a portion enters the instrument. This allows presenting the instrument with an extended source that can be quickly changed or illuminating it with a desirable source that would otherwise saturate the instrument. The final configuration is a Jones source, which was not used for WISE. Figure 3 shows WISE attached to MIC2.

Figure 3: WISE under testing attached to MIC2. WISE is the white at right held by the white support structure. MIC2 is the metallic cylinder at left.

While MIC2 was appropriate for most of the required testing, the MIC2 beam (21 x 11" oval) was not large enough to fill the WISE aperture and the absolute focus of MIC2 could not be determined to the level required for WISE. As a result, additional test setups were required for the focus and image quality testing. To measure focus requires a collimator with a moveable pinhole source. This is straightforward to setup on an optical table, but to illuminate a cryogenically cold instrument requires either placing the collimator in a cold vacuum chamber or illuminating the instrument through a window. The former requires significant hardware development, but the latter was possible with existing equipment.

The first setup used for measuring focus was to place the imager portion of WISE in a vacuum chamber and to find and adjust the focus of all four bands. The imager portion, which consists of the imaging optics, beam splitter assembly, and detectors, was built separately and available sooner than the telescope. Because it was available sooner and the telescope would be in approximate focus on arrival it was worthwhile focusing the imager. Since the imager had an aperture less

than two inches, obtaining a KBr window was straightforward and purchasing an approximately ND 7 filter was possible. The ND 7 filtering (with the filter cold) is required because of the extreme sensitivity of WISE; radiation from a 45 K blackbody saturates band 4 and room temperature radiation saturates all bands. At these optical density levels, it is difficult to manufacture a true ND filter, and the filter we obtained varied by more than an order through the spectral range, but this was acceptable for the focus testing.

To test the focus and image quality for the full WISE payload we used a larger collimator and a long, cooled tube (referred to as the Blue Tube) with the WISE instrument on one end and a window on the other. This test setup is shown in Figure 4. The Blue Tube is ~12 foot long with a 19" aperture and is cooled with flowing liquid nitrogen. Its purpose here is to prevent room temperature radiation from significantly warming and thereby distorting the WISE telescope which is designed to operate at ~12 K. The window was an available fused silica window of sufficient size. For filtering we used a sheet of singly aluminized Mylar which had an optical density of ~5. Modeling and testing showed the Mylar would not affect the image quality or focus. The window, however, does affect the focus because a radial temperature gradient develops in the window and the index of refraction changes with temperature. Care had to be taken to measure the gradient and properly account for this effect.

Figure 4: WISE (the white cryostat at right) under testing attached to the Blue Tube. The collimator used in the testing is on the optical bench in the foreground. The beam from this is directed into WISE by a large turning mirror just off the left edge of this picture.

The fused silica window used with the Blue Tube only transmits band 1 of WISE, and thus this setup could only be used to measure the focus and image quality for band 1. To determine the focus of the other bands, we used MIC2 to compare their focus position to that of band 1 after band 1 had been focused using the Blue Tube setup. For image quality, measurement for band 1 alone was deemed sufficient, since the WISE optics are all-reflective.

The complete set of characterization test setups thus consisted of:

- 1) The WISE imager in the chamber (twice)
- 2) WISE on the Blue Tube (three times)

- 3) WISE on MIC2
- 4) WISE on MIC2 a second time
- 5) WISE on the Blue Tube a final time

The last two tests were performed to show that WISE did not change after environmental tests (vibration testing and hydrogen fill tests) that were performed after WISE was tested with MIC2 the first time. The test flow is shown schematically in Figure 5.

Figure 5: Block diagram showing the WISE payload assembly and test flow. Components that are assembled are shown in the rounded boxes and integration steps are shown as light green blocks. The five characterization tests are shown in light blue with the intervening environmental testing shown as blue-green.

3. CHARACTERIZATION RESULTS

In general, the characterization results matched expectations and WISE was shown to meet performance requirements. The test results are too numerous to completely describe here, so presented here are the highlights of the focus, image quality, relative spectral response, and absolute response results and comparisons to on-orbit performance.

3.1 Focus

Finding focus was the most important characterization test since the WISE focus cannot be adjusted on-orbit, and thus must be correct prior to launch. It was the only test where adjustment was planned based on the results. First, focus was measured twice for the WISE imager in the chamber with the focus adjusted after each test. Focus was measured in all cases by moving the aperture of the collimator in steps through the position of best focus and collecting image data at each step. The position of best focus is determined by measuring the image quality. This is compared to the position of collimator focus and used with an optical model of the collimator-instrument combination to determine the change needed at the focal plane to bring the instrument into focus. An example focus curve is shown in Figure 6. In all cases where adjustment was needed, it was made by changing the size of the shim between the focal plane and its mount to the

imager assembly. The imager was not in best focus by the second test, but since the telescope had arrived and was not expected to be in perfect focus we moved on to the full payload testing.

Figure 6: A WISE Band 1 focus curve from the Blue Tube testing. At each collimator aperture positions, 5 images were collected and image quality measured separately for each image. Two image quality metrics are shown, ensquared energy (magenta circles, left axis) and noise pixels (blue triangles, right axis). The curves are parabola fits to the noise pixel and ensquared energy data. The variability observed at each position is due to variability in the spot shape from vibration or air currents in the room.

The WISE focus was tested three times on the Blue Tube and focus adjusted after the first two tests. Focusing was complete for band 1 when the third test showed it was in focus (this result is shown in Figure 7). While the band 2 to 4 focus could not be observed with the Blue Tube, the shims for these arrays were changed between Blue Tube tests based on the band 1 results and the observed differences between the bands in the last imager test. For both imager and full payload focus tests, the focus measurement required a day or two and shim adjustment one day, but the cold cycling involved required two to three weeks.

The focus of bands 2-4 was compared to band 1 when WISE was on MIC2 and bands 2-4 were found to be in focus to within the requirements. The re-testing on MIC2 and the Blue Tube after environmental testing showed there was no change in the focus. After WISE was launched, images obtained from orbit showed WISE to be in excellent focus.

Figure 7: The band 1 focus result prior to environmental testing. At each focal plane location where focus was measured, the plots show the distance in mils of shim increment required to bring a point into perfect focus. The variation seen here is mainly curvature in the focal plane, which was expected. The requirement for band 1 is to be in focus to within 2 mils.

3. 2 Image Quality

Image quality is an obviously important metric for instrument performance and was tested on the ground for requirements verification. It is found from the focus data by looking at the size of the observed spot (point response function) at best focus. For WISE, the image quality metric used was noise pixels which are defined by

$$N_p = \frac{(\sum V_{i,j})^2}{\sum V_{i,j}^2} \quad (1)$$

The $V_{i,j}$'s are the values on each pixel. Noise pixels can be thought of as a measure of how many pixels worth of noise there are in a measure of total source signal when the source is fitted with a point spread function. A smaller number signifies better image quality.

Near angle scatter (power from the source scattered away from the obvious spot, but within the field of view) can add significantly to the number of noise pixels. To better observe the low-level near-angle scatter, we performed a test where WISE collects data of the collimator source at a bright but not saturating signal level and then the source intensity is quickly increased by a factor of ~10x two times. The image data at all source brightnesses are combined to create a composite point response function with greater detail in the low-level wings. The resulting data (shown in figure 8) demonstrated that near angle scatter was not a significant factor in the number of noise pixels.

Figure 8: The WISE band 1 point response function shown on a logarithmic scale emphasizing the low level structure. The 46- pixel diameter circle is an artifact of the test setup (the aperture holder) and not part of the PRF.

The image quality results were difficult to interpret because the spot was affected by vibration or air currents in the room. This was obvious during data collection; the spot would visibly change shape and move slightly from image to subsequent image. The amount of motion varied from test to test and over time, but never ceased completely, nor could the source be determined. The best observed image quality result was ~ 13 noise pixels for band 1; while the expected value in this test configuration was ~ 10 .

Comparison with models showed the observed spot differed from expectations by having a larger FWHM while the near-angle scatter was not significantly different. It was not possible to match the images seen in the focus curves with an image quality model that used optical aberrations alone; to match the data a Gaussian blur had to be included. Taking the minimum amount of blur required to match the data to be a rough measure of the added vibration, we calculated the number of noise pixels without the blurring to be ~ 10.7 . With this result, we predicted that the WISE satellite would just meet its on-orbit image quality requirement of 14.5 noise pixels for band 1 (this value includes additional factors not present on the ground such as scan mirror motion uniformity and spacecraft jitter).

Figure 9: The WISE first light image shows the WISE image quality. (More images can be found at http://www.nasa.gov/mission_pages/WISE/main/index.html.)

On orbit measurements show the band 1 image quality to be 12.7 noise pixels. This is due in part to other effects being smaller than estimated but also because the effects of laboratory vibration were larger than our conservative estimate. Figure 9 shows the WISE first-light image. Band 2-4 image quality differs from band 1 only because of diffraction and all bands exceed their requirements.

3.3 Relative Spectral Response

The relative spectral response cannot be measured on orbit. Since accurate measurement of the ratio of signal in each band is of scientific importance for some objects, it is useful to know the true spectral response. In principle, the relative spectral response can be calculated from component data, but this is often not accurate in practice.

For in-band response, the MIC scatter source was illuminated by a Fourier Transform spectrometer at the MIC entrance port. The spectrometer operates in a step-scan mode where it steps its moving mirror and then holds steady for a set length. WISE data collection was synchronized with the spectrometer and thus WISE would collect an interferogram, which is Fourier transformed to provide a spectrum. This spectrum is compared to a spectrum of the MIC2 – spectrometer combination (taken in a prior test with a calibrated reference detector at the output) to give the relative spectral response of WISE in each of the bands. Further details on this method are described elsewhere². Data was collected simultaneously for bands 1 and 2 and separately for bands 3 and 4 because different spectrometer settings were required.

For out-of-band response, the collection is similar except instead of using the scatter source, the collimator source with a larger aperture is used to raise signal levels. Only a large spot near center of the field-of-view is illuminated instead of the whole array. Also, the available MIC2 cold spectral filters are used to block the in-band signal. Data was collected simultaneously for all bands that were blocked by the filter in use.

Figure 10: The in-band relative spectral response for all WISE bands.

Results are shown in Figures 10 and 11. The in-band response is about as expected except for reduced response at the short end of band 1 and the long end of band 4. The cause of this is unclear for band 1, but the spectral data is inconsistent with ice formation on the optics. For band 4, this is likely due to a detector cutoff shorter than expected. There was no observed change in response with position on the array. The out of band response was shown to meet requirements to the level of uncertainty in the measurements for all bands.

Figure 11: The in and out of band response for band 2 showing the component prediction (red), measured response (blue), measurement uncertainty (green), and requirement (orange).

3.4 Absolute Response

Absolute response is measured by observing the MIC2 extended source at a set of known temperatures (and thus known radiances). Images of the source are background subtracted, corrected for non-linearity and flat-fielded and the observed signal is compared to the integral of spectral radiance level multiplied by the relative spectral response. Since the extended source does not fill the instrument field of view a correction factor is required but this can be determined to better than 1% accuracy from the mechanical details of the WISE and MIC interface.

In all cases the measured absolute response was in reasonable agreement with expectations based on instrument transmission as calculated from component data and detector quantum efficiencies and electronics gains given the uncertainty in the measurements. Table 1 lists the measured responsivity at the wavelength of peak response in corrected counts (background subtracted, linearity corrected and flatfielded) per unit radiance and Figure 12 shows the response as a function of blackbody temperature for all 4 bands.

Table 1: WISE peak radiance response		
Band	Peak	Responsivity at Peak
1	3.48 μm	5.66×10^8 Cnts per $\text{W/m}^2\text{-sr}$
2	4.18 μm	4.93×10^8 Cnts per $\text{W/m}^2\text{-sr}$
3	14.4 μm	7.31×10^8 Cnts per $\text{W/m}^2\text{-sr}$
4	21.3 μm	1.03×10^9 Cnts per $\text{W/m}^2\text{-sr}$

Figure 12: The response of WISE to the MIC2 extended source. This is the initial quick-look at the data with little processing. Data both prior to and after the environmental tests is plotted and shows response did not change.

The radiance response is used with observed noise levels to determine instrument sensitivity. On-orbit measurements show that the bands 1-3 response is consistent with ground test results and the sensitivities meet requirements. The science team is still assessing the on band 4 on-orbit sensitivity.

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