Digital Imaging Space Camera (DISC) Design and Testing

Andrew Shumway, Mitch Whiteley, Jim Peterson, Quinn Young, Jed Hancock, James Peterson
Space Dynamics Laboratory, Utah State University Research Foundation
1695 North Research Park Way, North Logan, UT 84341; 435-797-4383
andrew.shumway@sdl.usu.edu
mitch.whiteley@sdl.usu.edu
jim.peterson@sdl.usu.edu
quinn.young@sdl.usu.edu
jed.hancock@sdl.usu.edu
james.peterson@sdl.usu.edu

ABSTRACT
A low-cost visible imaging camera was recently developed under internal funding at the Space Dynamics Laboratory (SDL). The Digital Imaging Space Camera (DISC) is a radiation-hardened, 1-megapixel visible imager specifically designed as an enabling technology for small satellites. Key parameters of the baseline design are: customizable optics; maximum full-frame rate, 10.43 fps @ 1 ms integration time; power dissipation, <2 watts; size, 87 x 70 x 230 mm (3.5 x 2.75 x 9.0”); and total mechanical mass, ~0.6 kg. The baseline design was fabricated and tested at SDL and performance was characterized through optical, radiometric, electrical, and thermal performance tests. The baseline design is presented along with test results.

INTRODUCTION
The Space Dynamics Laboratory (SDL) has a lengthy history designing, building, and calibrating imaging sensors. This experience was used to recognize and fill a need to develop a radiation-hardened, miniaturized visible imaging camera for space. At the time of development, SDL was not able to identify a single domestic provider of visible imagers capable of withstanding greater than 50 krad(Si) Total Ionizing Dose (TID). There was a need to develop a small, lightweight camera with high reliability, high radiation tolerance, simple interfaces, optical adaptability, and at a low cost. It is often difficult, if not impossible, to meet all design requests in a single system, so SDL attempted to make reasonable compromises in order to achieve a good balance of these design parameters.

The Digital Imaging Space Camera (DISC) was developed using design heritage from the SDL-designed, built, and tested SOFIE instrument. SOFIE is part of the NASA AIM mission that was launched in March 2007. The imaging system on SOFIE was used to image and track the sun in order to orient a series of detectors as they scan through the atmosphere’s layers. This camera was repackaged and redesigned as a breadboard unit, which was functionally tested to prove the design concept. Next the DISC baseline design was developed from these systems, then tested and characterized. The resulting third-generation DISC camera is a 1-megapixel visible imager designed specifically for small satellite applications. This baseline design DISC imager is shown in Figure 1.

Figure 1: The Digital Imaging Space Camera (DISC) is a small radiation-hardened 1-megapixel monochromatic visible imager weighing only 600 grams and consuming less than 2 W.

The DISC camera provides monochromatic 1024 x 1024 pixel images with a system that was designed from the ground up to be tolerant to the rigors of the space environment. At the component level, the electronics are rated at a radiation hardness assurance level no less than 100 krad(Si). With a 100 mil minimum shielding thickness, and using radiation-tolerant glass, the imager can withstand multi-year operations in high radiation orbits or deep space.
Multiple uses are anticipated, including space situational awareness missions and rendezvous and docking operations (such as a sample return mission from the Moon or Mars).

**DESIGN DESCRIPTION**

The black anodized aluminum camera housing is ~0.6 kg with overall dimensions of 87 x 70 x 230 mm (3.5 x 2.75 x 9.0") and a mounting base of 70 x 165 mm (2.75 x 6.5") as shown in Figure 2.

![Figure 2: Overall Dimensions](image)

The baseline optical design uses four lenses, a fold mirror, and a spectral filter, but is customizable according to mission needs. The optics are packaged in a housing with established purge paths, filtered vents, and a purge line all designed to control contamination during handling and test operations. A combination of external and internal baffles is used to reduce stray light on the focal plane array (FPA). The electronics board is housed in an aluminum case with 0.1”-thick walls for radiation protection.

**Electronics Design**

The electronics design is built entirely from space-flight qualified components. The electronics board supports the FPA in the image plane below the fold mirror and is controlled by an Actel RTAX1000S field programmable gate array (FPGA) mounted to the underside, as shown in Figures 2 and 3.

![Figure 2: Electronics board with FPA and FPGA](image)

The sensor used is the STAR-1000, a 1-megapixel radiation-hardened CMOS visible monochromatic FPA manufactured by Cypress/FillFactory. It was selected because of its radiation tolerance, among other features. The FPA is capable of windowing, pixel binning, fixed pattern noise (FPN) correction, and has dual-slope integration. An on-board 10-bit analog-to-digital converter (ADC) is used to digitize the pixel values. It has a 15 μm pixel pitch with a 44% fill factor (FF). The fill factor and quantum efficiency (QE) together produce an overall efficiency of ~22% in the spectral region from 500 to 700 nm, which is selected by a spectral filter in the optical design.

The frame rate is 10.4 fps for the full 1024 x 1024 image size. Faster rates for sub-images are shown in Table 1.

**Table 1: Frame Rate versus Frame Size for 1 ms integration time**

<table>
<thead>
<tr>
<th>Frame Size</th>
<th>Frames per Second (fps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1024 X 1024</td>
<td>10.4</td>
</tr>
<tr>
<td>512 X 512</td>
<td>37.6</td>
</tr>
<tr>
<td>256 X 256</td>
<td>120.1</td>
</tr>
<tr>
<td>64 X 64</td>
<td>553.9</td>
</tr>
</tbody>
</table>

![Table 1: Frame Rate versus Frame Size for 1 ms integration time](image)

The camera interface is based on the Camera Link® standard for high speed digital cameras, which is compatible with industry standard TIA/EIA-644 LVDS. The interface differs from Camera Link® in that it uses a 21:3 LVDS radiation-hardened serializer. In addition to the 10-bit pixel data, a 32-bit Free Running Timer (FRT) is encoded into the data stream.

A full duplex LVDS UART command and control interface is available in 9600, 38400, 57600, or 115200 baud with either odd or no parity. Serial baud rate and parity are selected at circuit board build time and not changeable after launch.
There are 18 16-bit control and status registers in the camera, which are configured with a 3-byte write command and read back with a 1-byte read command. There are four camera control discrete digital inputs, only three of which are currently used. These inputs enable a video imaging mode, a snapshot mode, and reset the FRT. The FPGA controls the electronics and implements numerous configuration registers for flexible mission operations.

The DISC electronic architecture block diagram is shown in Figure 4. All external interfaces to DISC are through the 37-pin Micro-D connector. Externally regulated power is required at 12 VDC and 5 VDC. The power consumption is < 2 watts. Power and data interfacing can optionally be provided by the SDL Modular Avionics System (MODAS), which takes full advantage of the FPA operational features.

**Figure 4: Electronic architecture block diagram**

**Optics Design**

The design objective established for the baseline optical system was to provide for high resolution imagery of objects over a specified object range, at minimized size, cost, and complexity. The baseline design, shown in Figure 5, employs an optimized ‘double-gauss’ layout containing four individual lenses, and a bandpass filter. The baseline design is optimized for image performance over the temperature range of -10°C to +50°C. The field of view, aperture size, and focus distance are adjustable according to mission needs and are traded with parameters such as integration time and image quality. The optics are constructed with radiation-tolerant glass and coated with anti-reflective coatings in order to reduce stray light and improve optical throughput to ~75%.

**Figure 5: Baseline optical raytrace design of DISC imager**

A 500 to 700 nm bandpass filter was used to reduce chromatic aberrations and improve the image quality. This filter is tilted in order to eliminate a stray light path to the FPA.

**Mechanical / Thermal Design**

The structural design requirement chosen for the DISC imager is to survive launch loads up to 17.3 gRMS. A structural analysis was performed on the electronics board, which calculated the lowest bending mode to be 1120 Hz, as shown in Figure 6.

**Figure 6: Electronics board structural analysis showing first mode at 1120 Hz with 3σ deflection**

The structural analysis on the electronic board indicated the need to increase the flight qualification levels used to test some of the capacitors, some resistors, one diode and the connector. In lieu of performing qualification testing on individual parts, a flight board will soon be qualification tested.

With the structural analysis completed for the electronics board and testing pending, a structural
analysis will also be performed for the full DISC imager including housing and optics.

An electronics board level thermal analysis was performed using an interface temperature of 70ºC where the board bolts to the housing. Power was applied to various regions over the board in the thermal model representing power dissipation of individual electronic components as shown in Figure 7. Subsequent power measurements on the electronics board showed that the power used in the analysis was conservative.

**Figure 7: Power distribution over electronics board**

The resulting temperature gradient profile shown in Figure 8 reveals the hottest location to be 75ºC under the linear regulator. The temperature gradient under the FPA was 0.8ºC with a maximum temperature of 73ºC. Using the 75ºC maximum board temperature as the temperature under all components, maximum component temperatures were found. The LVDS Dual Tx/Rx component was predicted to be the warmest at 94.4ºC, and with 15.6ºC margin to the derated allowable temperature. The STAR 1000 FPA was predicted to operate at 77.1ºC, but had the least margin with 8.7ºC.

**Figure 8: Temperature gradients across electronics board show maximum temperature of 75ºC**

**SYSTEM-LEVEL TESTING**

A baseline version of the DISC imager was built and tested in a series of optical, radiometric, and thermal tests. Overall test set-ups and top-level results are given below.

**Optical Tests**

Optical tests were performed to characterize spatial imaging performance, optical distortion, and stray light performance.

**Spatial Imaging Performance**

Spatial imaging performance was measured by imaging a bar-pattern target shown in Figure 9 and computing the contrast transfer function (CTF) from these data. A bar target pattern was chosen as a convenient method to verify system performance, although the motivation of this measurement was to estimate the system modulation transfer function (MTF) and to validate the system-level MTF model of the DISC imager, which includes models of the optics and FPA.

The MTF is a standard metric used to describe system imaging characteristics of extended scenes. A particular MTF frequency can be expressed by an infinite sum of CTF measurements. Conversion from CTF to MTF must be performed with great care because of effects of aliasing, phasing, etc. However, for the purpose of our system verification, the MTF can be related to the CTF for frequencies above 1/3 the system cutoff frequency by the following approximation:

\[
MTF \approx CTF \cdot \frac{\pi}{4} \tag{1}
\]

Similarly, for frequencies below 1/3 the system cutoff frequency, the relationship is:

\[
MTF \approx CTF \tag{2}
\]

The CTF was computed for a range of target distances with the maximized CTF indicating best focus distance of the baseline optical design.

**Figure 9: Bar pattern target used for CTF measurements showing contrast mask used for brightness correction**
Because of variations in lighting across the face of the target, a brightness correction was made by mapping out variations both across the white surface and across in the dark surfaces. This allowed the CTF to be computed more accurately. As shown in Figure 10, the CTF was computed for data collected at 20°C while varying the target distance. Distance “A” proved to be the best focus because the CTF values were maximized at this distance. These CTF results were calculated for the vertical bars corresponding to the DISC imager Y axis. It was understood that the MTF for the STAR-1000 sensor is direction dependent, and thus important to measure in each imager axis.

As evident in Figure 11, the CTF was reduced, indicating increased blur at a given spatial frequency. In Figure 11, CTF values were low enough near the Nyquist frequency that the CTF derivation may possibly be dominated by measurements uncertainties. These measurements were next compared to modeled predictions.

In order to predict the spatial imaging performance of the DISC camera system, the MTF of the optics and FPA were modeled. The MTF of the optics was modeled as a circular clear aperture lens, with assumed system aberrations. The MTF of the FPA detector was modeled considering the pixel geometry, fill factor, and effects of diffusion.

The CTF was also calculated for the DISC imager X axis in order to characterize directional dependence. These same images were processed, but this time the horizontal bar patterns were used to compute the CTF.

As evident in Figure 11, the CTF was reduced, indicating increased blur at a given spatial frequency. In Figure 11, CTF values were low enough near the Nyquist frequency that the CTF derivation may possibly be dominated by measurements uncertainties. These measurements were next compared to modeled predictions.

In order to predict the spatial imaging performance of the DISC camera system, the MTF of the optics and FPA were modeled. The MTF of the optics was modeled as a circular clear aperture lens, with assumed system aberrations. The MTF of the FPA detector was modeled considering the pixel geometry, fill factor, and effects of diffusion.
Figure 13: System-level comparison of the modeled MTF and measured CTF (horizontal bars & imager Y). The measured CTF has been adjusted to approximate an MTF.

With the DISC imager in the thermal-vacuum chamber, the temperature was varied from -30º to +70ºC while the target images in the best focus position were collected. The CTF for each of these temperatures was computed to see how the image quality varied with temperature. As noted on Figure 14, no significant variation with temperature was observed, which indicates that the design was properly optimized for this temperature range.

Figure 14: CTF in non-readout direction for best focus distance as a function of temperature

Optical Distortion

The optical distortion was measured using the autocollimation source of a theodolite looking into the camera optics. With the source imaged on the FPA, the pixel coordinates as well as the theodolite angle could be logged over the spatial map.

Figure 15: Percent optical distortion across the field sampled in a 5x5 grid

The optical distortion results are shown in Figure 15. The distortion result was <0.7%, which compared well to the modeled prediction.

Stray Light

Stray light was characterized in two different ways. The first approach used a lightbulb source placed imaged in a darkened lab. Images were taken with the source positioned at various angles with respect to boresight. The source was modulated so the background signals could be subtracted. These data were normalized to the response of the imager staring at the lightbulb source. This setup was not as restrictive as the sun off-axis measurements made with a different setup, and allowed stray light to be measured at angles from 0º to 20º off-axis. Data from this test is shown in Figure 17.

For the second set of measurements, direct sunlight was used to illuminate the DISC baffle while response as a function of incident angle was measured. As shown in Figure 16, the camera was placed on a two-axis rotary stage to track and position the boresight with respect to the sun. With the DISC imager always looking into the Dark Target regardless of incident angle to the sun, a nearly constant signal was measured for light in the on-axis direction. Signal changes were attributed to response to off-axis sunlight. The imager was first centered on the sun and then moved off-axis while the response was recorded. The response was background-subtracted using data with the DISC baffle shaded at each angle. The corrected response was then normalized to the response when looking through a pinhole aperture directly at the sun, after separately characterizing the pinhole attenuation.
Figure 16: Disc imager viewing Dark Target mounted on stage for Sun Off-Axis measurements

Data from both measurements are plotted together in Figure 17. The sun response data was limited to angles beyond 20º incidence because of the shadow of the Dark Target being cast on the DISC baffle. On the other hand, the lightbulb source data was only usable up to 20º or so because of the relatively dim source when compared to the sun. For the lightbulb source measurements, the scan was in the horizontal direction with respect to the camera axis. This data matches well with the horizontal data scan from the sun response as evident in Figure 17. The vertical response data was larger due to the baffling design. A glint was also measured between 5º and 10º off axis. This glint will be analyzed during future work planned for the next phase of development.

Figure 17: Stray light response normalized to on-axis source

Radiometric Tests

Radiometric tests were performed to measure responsivity, linearity, dark current, random noise, and spatial uniformity.

Figure 18: DISC imager inside thermal-vacuum chamber viewing integrating sphere

Radiometric tests were performed to measure responsivity, linearity, dark current, random noise, and spatial uniformity. Radiance responsivity was measured over a range of temperatures by presenting a calibrated integrating sphere to the DISC imager while mounted inside a thermal-vacuum chamber, as shown in Figure 18.

Performing this absolute responsivity measurement enabled the camera gain \( K \) in electrons per count to be derived from test data combined with \textit{a priori} knowledge of the fill factor and the quantum efficiency. Measurements of the ADC gain enabled calculation of the pixel sensitivity \( S_V \) in volts per electron. These parameters compared well to manufacturer specifications. Of particular note is the photo-voltaic response curve reproduced from these measurements and shown in Figure 19. This curve reveals the detector voltage response to electrons and shows the detector approaching saturation; it also shows the number of electrons that can be accumulated by the detector in a full-well condition. This curve compared well with manufacturer’s data.

Figure 19: Detector response curve

Radiance responsivity was found to be repeatable within a few percent from -30ºC to +50ºC and then increase by 15% at +70ºC. Further investigation is warranted to study this increase above +50ºC.
Linearity

The linearity was calculated from data produced with the DISC imager viewing a source and varying the integration time to produce a signal covering the dynamic range. As shown in Figure 20, the system is linear within 5% over most of the dynamic range. This compares well with manufacturer’s data on the sensor.

Random Noise

The read noise was measured at the shortest integration time of 3.8 μsec with all light blocked from entering the DISC imager. The RMS value of pixel noise was measured at 0.4 counts (1σ) in this condition. The RMS noise increased from this point over the dynamic range as light was exposed to the imager and as the integration time was increased. The maximum RMS noise measured high in the dynamic range, but before saturation occurred, was 1.2 counts (1σ). This noise component amounts to 0.1% of the 1024 count total range.

Spatial Uniformity

The spatial uniformity is driven by the uniformity of the optical system and uniformity of individual pixel responsivities. Measurements were performed by directly illuminating the FPA with a uniform LED source without any optics in the path, as shown in Figure 23.
Figure 23. Results from this test showed the uniformity to be approximately 1.5% (1σ) of the FPA alone.

A system-level test was performed to characterize uniformity of the optics and FPA together as a system. Multiple frames were collected while viewing an integrating sphere. As with the previous test, the mean value of all the frames was found and the variation over the frame was computed. This time, the variation was approximately 3% (1σ). The increase in non-uniformity is attributed to the behavior of the optics, as shown in the high-contrast image in Figure 24.

Environmental Tests

The DISC imager was installed in a thermal-vacuum chamber where it was subjected to eight thermal cycles from -30°C to +70°C as shown in Figure 25. Spatial imaging tests as well as system noise, dark current, and responsivity were measured at various temperatures over this range. The DISC imager experienced this thermal environment with no detected problems.

A qualitative-level Electromagnetic Interference (EMI) test was also performed on the DISC imager with no apparent issues, but a comprehensive test is yet to be performed following the MIL-STD-461.

SUMMARY AND FUTURE WORK

Additional funding has been set aside for the next SDL fiscal year for further improvements and testing on the DISC design. Future work identified is the development of an improved lens mount design for ease of assembly and reliability, and also better understanding of stray light performance through modeling and testing. To complete the space-flight qualification tests, the structural modeling needs to be completed and testing needs to be performed.

ACKNOWLEDGEMENTS

The authors express their sincere appreciation to the following individuals for their significant contributions to the DISC development: Melissa Draper, Weston Allen, mechanical design; Brian Thompson, structural and thermal analysis; Pat Patterson, trade studies and conceptual design & development; Val King, mechanical technologist. The authors also appreciate the funding and support from the Research Division of SDL, directed by Dr. J. Steven Hansen and Dr. Scott Jensen.

References