

DISC Experiment Overview and On-Orbit Performance Results

Andrew Nicholas, Ted Finne, Ivan Galysh, Ed Kline
 Naval Research Laboratory
 4555 Overlook Ave., Washington, DC 20375; 202-767-2441
 andrew.nicholas@nrl.navy.mil

Mitch Whiteley, Chad Fish, Weston Allen, Steven Grover, Jim Peterson, Bryan Bingham
 Space Dynamics Laboratory, Utah State University
 1695 N. Research Park Way, North Logan, UT 84341; 435-713-3483
 mitch.whiteley@sdl.usu.edu

ABSTRACT

The Digital Imaging Star Camera (DISC) experiment has successfully imaged star fields from the International Space Station (ISS). DISC is a Naval Research Laboratory (NRL) led payload developed jointly by NRL and the Utah State University Space Dynamics Laboratory (SDL) to advance miniaturized technology for accurate precision pointing knowledge in space which is a critical mission requirement for many scientific and operational payloads. The low size, weight and power (<10x10x10 cm, <1kg, <1 W) sensing platform that will provide an enhanced pointing capability for nano- and pico- satellite busses. It is flying on the ISS as part of the Air Force Space Test Program STP-H3 flight to provide a proof of concept for DISC experiment. This technology represents a key transition from large, high cost, long-timescale programs to small, low-cost, rapid response science enabling sensing platforms. This paper will focus on the instrument design and on-orbit mission performance.

INTRODUCTION

Accurate precision pointing knowledge is a critical mission requirement for many scientific and operational payloads in space. A low Size Weight And Power (SWAP) pointing sensor will provide a science enabling technology on pico- and nano-satellite platforms for payloads with stringent pointing requirements. One such example is the ability to measure ion drift velocities in the upper atmosphere on a small satellite, which would require pointing knowledge of 0.02 degrees to measure ion drifts of 5-10 m/s. Traditional star trackers (0.0027 degrees) require too large a footprint, more mass and more power than is available on a nano- or pico- satellite bus. A combination of horizon sensors and sun sensors will meet the SWAP requirements but have insufficient pointing resolution (~0.2 degrees). The development of a low SWAP pointing sensor with sufficient resolution (0.02 degrees) would enhance a small satellite bus to be a viable scientific sensing platform.

The primary objective is to demonstrate a low size, weight and power stellar aspect camera for integration into nano- and pico-satellites that is capable of

measuring providing pointing accuracies of 0.02 degrees or better. The DISC payload was integrated into a suite of experiments flown by the DoD Space Test Program (STP) as STP-H3 flight, which provides a proof of concept for DISC experiment. The STP-H3 suite was launched aboard STS-134 (Endeavour) on 16 May 2011 and the suite was installed on the International Space Station on P3 truss as part of the Express Logistics Carrier 3(ELC-3) in the FRAM-8 (keel side) position.

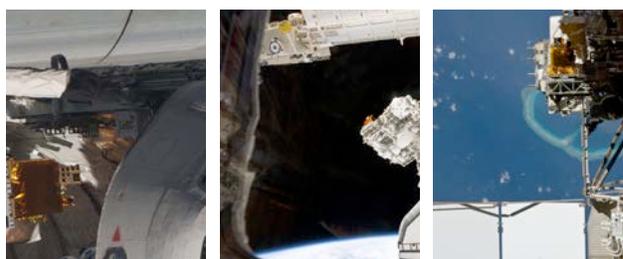


Figure 1: DISC on the ELC-3 in the Cargo Bay (left), during removal from Cargo Bay (center), and installed on the P3 Truss (right). Photos courtesy of NASA.

DESIGN

Camera Design

The DISC camera electronics were designed around a radiation-tolerant 1024×1024 CMOS active pixel sensor from FillFactory/Cypress Electronics (part no. CYIH1SM1000AA-HHCS). The image sensor supports correlated double sampling with a 12-bit ADC included on the die. An FPGA was programmed to interface to the sensor and store images in onboard memory. External command and control, including the downloading of images, was accomplished via SpaceWire.

The chassis for the DISC camera was sized to fit within a CubeSat payload deck (96×96×70 mm). Inside the chassis, the camera electronics were folded around the opto-mechanical structure (see Figure 2). Radiometric analysis of the camera showed the capability to resolve stars down to magnitude-6 with an integration time of 20 ms.

However, due to schedule and cost constraints, the custom optics were replaced with a COTS camera lens. The Carl Zeiss Planar T* 1.4/85 ZF was selected. It should also be noted that the lens was completely disassembled, precision cleaned, reassembled, and staked prior to environmental qualifications (see Figure 3). Additional analysis with the COTS lens showed camera integration time would need to increase to 30-40 ms to resolve magnitude-6 stars.

Finally, a bi-stable shutter from Brandstorm Instruments was installed for protection against sun staring.

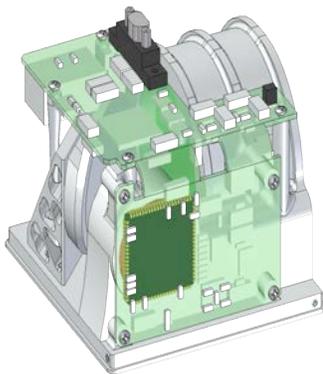


Figure 2: DISC Star Camera with Custom Optical Design.

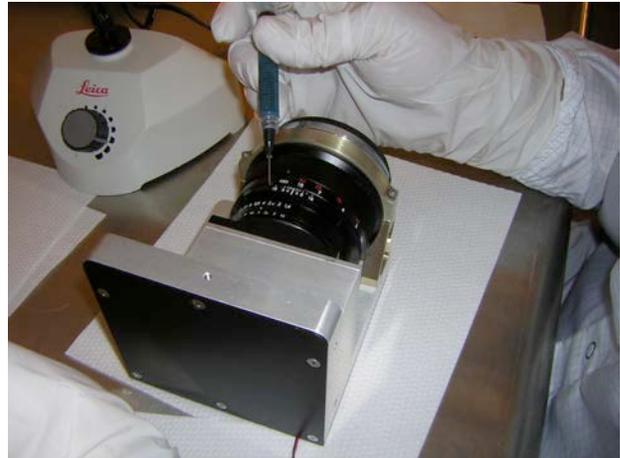


Figure 3: DISC Star Camera with COTS lens.

Mechanical Design

The star camera was integrated into a frame that enclosed the camera and a payload interface board that communicates between the camera and the ISS. The payload dimensions are 15.24 x 18.42 x 21.46 cm with a recorded mass of 2.83 kg as seen in Figure 4. The camera system is designed for the 10x10x10 cm volume class of CubeSat, while the support structure was increased in size to meet ISS safety requirements.

The structure design allowed for ease of access to internal components, which was achieved by the assembly of a skeleton sub-structure that could contain the internal assembly without the structure closeout panels in place. The substructure is comprised of four right-angled aluminum corner longerons that are pinned at the top, mid, and base plane by stiffening decks. The decks were also used as mounting surfaces for internal hardware and electronics. The outer panels of the structure attach to the sub-structure to cover and protect internal components, as well as add structure stiffness.

One of the four longerons could be removed independently of the remaining sub-structure, which would allow for the installation and removal of either the camera or the electronics assembly independently of each other.

Passive thermal coatings were specified for the aluminum closeout panels. Black and clear anodized panels act as heat absorbers and radiators, while an MLI blanket covered all surfaces except the clear anodized radiators for thermal stabilization. Internal Kapton strip heaters and bi-metallic thermostats helped control system temperatures actively within the camera sensors active efficiency range.

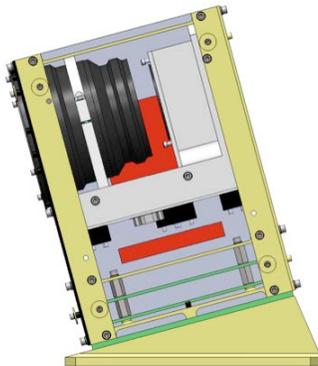
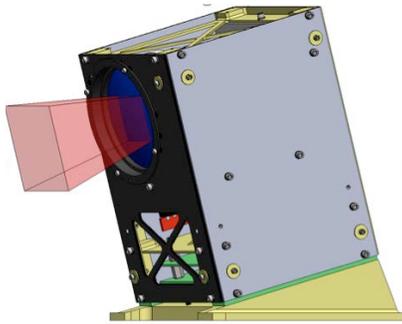


Figure 4: Top: DISC mechanical layout depicting 20 x 20 deg FOV. Center: camera placement, active thermal control (red) and payload interface boards (green). Bottom: pre-flight photo after thermal blanket installation.

Payload Interface Design

The payload interface consists of two circuit boards, one for power and the second the digital electronics. The power board contains an EMI Filter module and a DC-DC converter to provide 5 volts to the digital electronics board.

The digital electronics board, named the payload interface board (PIB), interfaces the camera to the ISS. The ISS interface is a RS-422 UART interface at 115200 bits/sec. The Space Test Program developed a palette providing a UART interface to multiple

payloads and moves the data to the ISS 1553 data bus. The PIB uses an NXP ARM processor to control the camera, extract images and data from the camera and move the data to the ISS.

The camera interface uses SpaceWire, which is implemented in an IGLOO FPGA. The FPGA interfaces to the processor through a 16-bit data bus. Images are moved from the camera to external FLASH memory. When commanded, the images are sent to the ISS in 1 Kbyte packets.

The flight software uses an open source real time kernel called tnKernal. It is a small multi-tasking kernel for multiple ARM processors. One task handles the command and data interface and the second task controls the camera.

Camera operations are performed by scripts. The scripts control the shutter, sensor exposure time, time delay between images, camera configuration, and moving data from the camera to the FLASH memory.

OPERATIONS

The DISC Payload Operations Center (POC) at the NRL provides command and telemetry access to the DISC experiment. Command access to the DISC experiment is established via a secure VPN connection to NASA's facilities at the Marshall Space Flight Center (MSFC). By coordinating with NASA operators using a voice over IP service, DISC operators enable a secure connection to NASA's network services. Python interfaces, written at the NRL, utilize the Telemetry Resource Kit (TReK) APIs, provided by NASA, to build CCSDS packets containing commands for DISC. Commands are then sent to systems at the MSFC where they are verified against defined commands and then transmitted over S-Band to the International Space Station using a Tracking and Data Relay system (TDRSS). Upon receipt at the ISS, the CCSDS packets are routed to the STPH3 payload where an internal router delivers the command contained in the CCSDS packet to the DISC experiment.

Telemetry from DISC is packaged into CCSDS packets by the STPH3 payload and then transmitted over KU-Band to the TDRSS and then to ground stations and then on to the MSFC in Huntsville, Alabama. The MSFC records the incoming telemetry and then forwards it on to the DISC POC using UDP packets. NASA also provides web services enabling DISC operators to retrieve recorded data via FTP. Upon receipt at the DISC POC at the NRL, DISC telemetry is extracted from the STPH3 CCSDS packets, which contain telemetry for 3 other science experiments

besides DISC. Images and register data are then extracted from the DISC telemetry and sent via email to Utah State University for image analysis. ISS telemetry for time of image acquisition and Satellite Tool Kit models provided by STP supply pointing information to confirm the results of image analysis.

ANALYSIS

Image Analysis

The mission of the DISC Star Camera was to advance miniaturized technology for accurate precision pointing knowledge in space. Images taken by the DISC on the ISS were ground processed by a star-tracking algorithm developed by the Space Dynamics Laboratory to characterize this capability. The star-tracking algorithm matches the image geometric information from the resolvable stars to the Hipparcos Star Catalog¹ (see Figure 5). The algorithm outputs a quaternion that rotates the bore of each image to the J2000 inertial coordinate frame of the star catalog.

Following the identification of stars, error analysis between the image's computed position of each star and the star catalog's position was performed. The results of this analysis provide a metric for the DISC Star Camera's optical accuracy. It should be noted that no calibration or distortion mapping was completed on the COTS lens prior to the mission. Therefore, the results of the error analysis were completed without any corrections.

The image analysis set included 145 images downloaded from the ISS. All of them were taken at full resolution, 1024×1024. Star identification successfully completed on all but 10 of those images. Further analysis is needed to determine why, however, possible reasons are data corruption and false stars (satellites, planets, etc.). Figure 6 plots the distribution of the star position errors. Table 1 presents the results of the image error analysis.

As presented in Table 1 the average error was 0.02°. These results are well received given the goal of the experiment and the fact that no calibration or corrections are being applied to the images. Had calibration been able to take place or a distortion map been created, accuracy would have been significantly better.

Additional efforts to build a custom set of lens would improve the accuracy more than an order of magnitude. Figure 7 compares aberrations and spot sizes between

the custom lens and the COTS lens flown for this mission. The spot size for COTS lens is 200× larger than the diffraction limit for this system. The custom lens would have produced images at least 25× better than the COTS system.

Recall the radiometric study predicted the integration (or exposure) time to resolve stars down to magnitude-6 would need to increase beyond the 20 ms with the COTS lens. However, at least in the small set of images processed, an integration time of 20 ms was still adequate to identify a number of stars between magnitude-5 and 6. Images with 40, 30, and 20 ms integration times were part of the analysis.

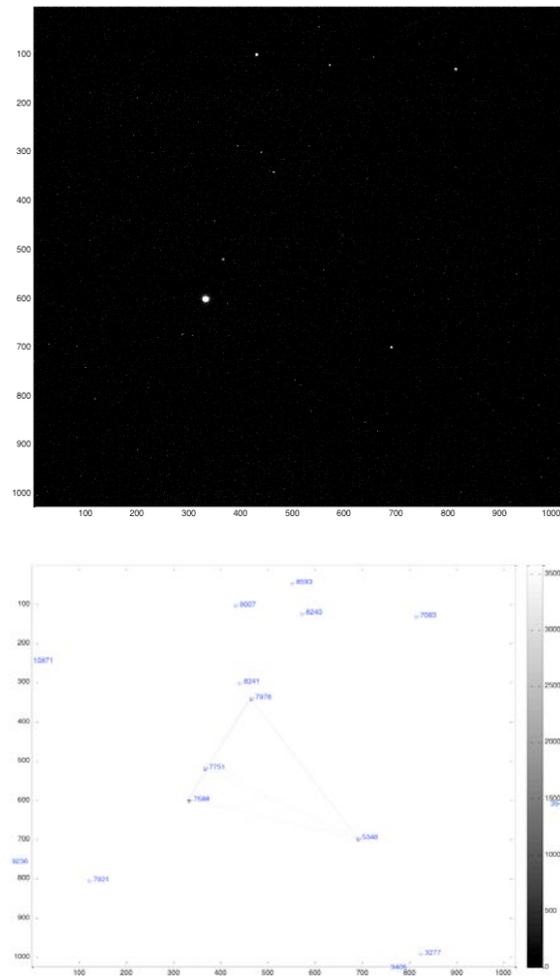


Figure 5: Actual DISC Image from the ISS matched against the Hipparcos Star Catalog.

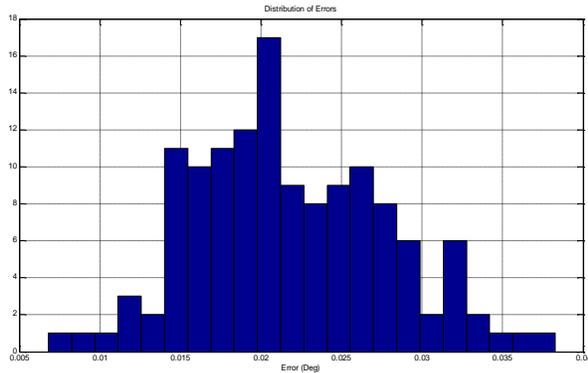


Figure 6: Distribution of star ID errors.

Table 1: DISC Star Image Analysis

Number of Images	Number of Matches	Match Rate	Average Error (°)	Std. Dev. Error (°) 3σ
145	125	93.1%	0.0217°	0.0177°

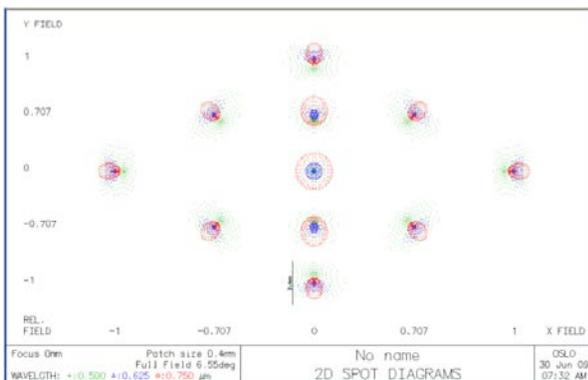
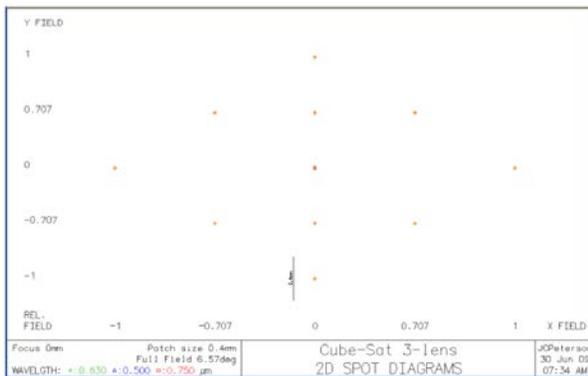


Figure 7: Comparison of spot diagram between custom (top) and COTS (bottom).

Attitude Verification

In order to verify the star identification an independent measurement of attitude was used. The attitude of the DISC imager at the time certain images were taken was desired. The attitude at the times of interest was calculated as a combination of several direction cosine rotation matrices.

The first required rotation matrix was the rotation matrix from the inertial J2000 reference frame to the nadir pointing orbital reference frame of the international space station. This rotation matrix was obtained from the STK software program by AGI.

The second required rotation matrix was the rotation matrix from the orbital reference frame to the body axes of the international space station at the times of interest. STP provided this rotation matrix.

The third required rotation matrix was the rotation matrix from the body axes of the international space station to the mounting orientation of the DISC camera. These were given as pitch, roll, and yaw angles, from which a direction cosine rotation matrix was created. STP also provided these angles.

The fourth and final rotation matrix was rotation from the mounting orientation of the DISC camera (Figure 8) to the internally defined reference frame for the DISC camera. All of the attitude calculations were performed in the DISC Camera reference frame.

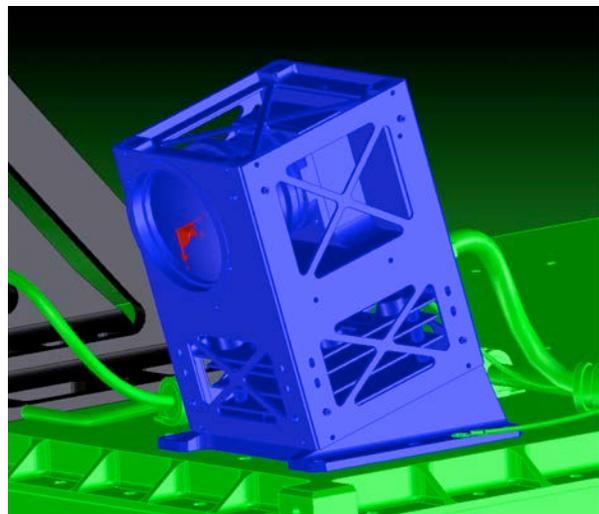


Figure 8: Mounting orientation of DISC on the International Space Station.

By combining all four of these rotation matrices, a complete rotation matrix from the inertial J2000 reference frame to the internal DISC camera reference frame was created for the times of interest.

Results

Comparing the calculated attitude from the DISC images to the expected attitude using the data from STK and NASA yielded the results in Table 2.

Table 2: DISC Attitude Verification Results

Average Deviation (°)	Standard Deviation (°) 3σ
0.888°	1.148 °

The comparison of the attitude calculated with the DISC camera with the expected attitude yielded extremely good results. There are a number of sources of error in the expected attitude. The data for the expected attitude was pulled from three different sources, which may not have been perfectly correlated. There are also inherent errors in the sources, such as orbital position errors, unaccounted mounting offsets, and timing errors in the actual image acquisition time. Even with all of these sources of error the overall deviation between the calculated and expected attitude is less than 1 degree as seen in Figure 9.

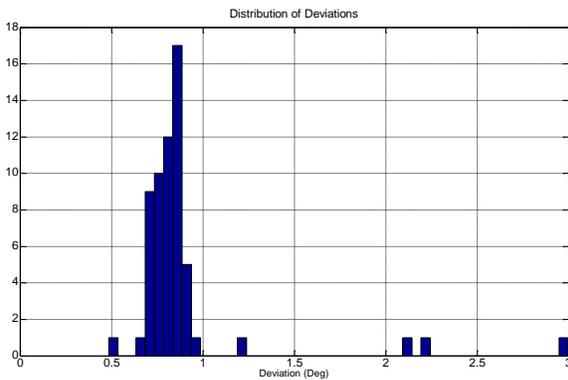


Figure 9: Distributions of deviations from expected attitude.

CONCLUSIONS

The DISC instrument was launched on May 16, 2011 as part of the STP-H3 suite on ELC-3 and installed on the International Space Station. The instrument passed initial functional checkout and is currently capturing star field images from the ISS daily. The sensor has performed exceptionally with an average pointing error of 0.02 degrees meeting the program expectation. With

future optics and processing upgrades it is expected that the results could be improved by an order of magnitude or more. This technology represents a key transition from large, high cost, long-timescale programs to small, low-cost, rapid response science enabling sensing platforms.

Acknowledgments

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References

1. Hipparcos Star Catalog
<http://www.rssd.esa.int/index.php?project=HIPPARCOS&page=Overview>