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An Agile Multi-use Nano Star Camera for Constellation Applications

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ABSTRACT

Precision attitude control is a fundamental need in many constellation applications both for station-keeping and mission operations. To achieve arc-second pointing a star camera is required, however current camera systems available for nanosatellites have limited arc-minute performance and are solely purposed for attitude solutions. The Blue Canyon Technologies (BCT) Nano Star Camera-1 (NSC-1) is a small nanosatellite form factor star camera that has multiple dynamic modes of operation. The first and primary function of the NSC-1 is to provide star-light-in-quaternion-out attitude estimates, which it does at a rate of 5Hz with an accuracy of 0.002 degrees (7 arc-seconds), 1-sigma. The second function of the NSC-1 is to provide full-field images, with resolution greater than 1 mega-pixel. The images can be provided to the host at 1Hz to support functions such as pose determination for RPOD. Akin to typical hand-held cameras, the NSC-1 supports multiple exposure methods to maximize image quality of the object being viewed. It also supports multiple dynamic regions of interest that can be controlled independently, to optimize the image of an object while simultaneously viewing stars for attitude. The third function of the NSC-1 is to support space situational awareness (SSA) applications. The NSC-1 automatically detects objects moving relative to the star field and reports the information to the host spacecraft. Operating in the SSA mode, spacecraft can utilize the NSC-1 for vision based relative navigation applications.

INTRODUCTION

Nano-satellites, and in particularly CubeSats, have grown significantly in popularity over the past decade due in large part to the availability of secondary launch opportunities and the development of a standard interface[1]. Early CubeSats were relatively rudimentary and lacked high rate communications, precision attitude control and deployable solar arrays. These systems were also largely without a science focus. In recent years, based on the success of the National Science Foundation CubeSat program the science yield on these CubeSats has increased dramatically[2]. The results from the Radio Auroral Explorer (RAX-2), the Colorado Student Space Weather Experiment (CSSWE) and the Dynamic Ionosphere CubeSat Experiment (DICE) have all made significant scientific contributions[3,4,5] and have clearly shown the utility of CubeSats to conduct cutting edge science missions.

One of the key subsystems necessary to enable future science missions is a precision attitude determination and control system. Accurate bus pointing to sub arc-minute levels will enable new space physics, astronomy and earth observing missions with CubeSats. Such increased pointing will also enable the use of narrow beam directional antennas for satellite-to-satellite cross-links and high rate data downlinks. While gyros, magnetometers, sun sensors and earth horizon crossing indicators can be utilized for attitude determination the fidelity of the attitude solution utilizing these components is typically on the order of 0.5°. To achieve sub arc-minute level pointing determination a star camera is required.

MOTIVATION

Future nano-satellite and CubeSat missions are moving towards earth observation and constellations that require precision pointing, better than 1 arc minute, to achieve their mission goals.

Earth Observing Missions

The Earth Observing (EO) mission NigeriaSat-2 was designed to achieve 2.5m imagery in a panchromatic waveband along with 5m and 32m imagery in four multi-spectral channels[6]. Such EO missions have stringent requirements on attitude knowledge for geolocation of observations. A 1 arc-minute error in pointing knowledge will correspond to a 175m error in ground position for a satellite operating in low earth orbit (LEO) at 600km. Using ground image tie-points the geolocation can be improved. With scene sizes on the order of 10kmx10km (0.5m pixel resolution with 2048x2048 imager), a star tracker capable of 20 arc second pointing knowledge will provide sufficient overlap for constrained geolocation ground processing.

Space Weather Missions

Space Weather missions measuring the in-situ ionospheric and thermospheric winds, temperatures and composition require precise pointing to accurately measure the geophysical flow and separate this term from the spacecraft velocity vector[7].

$$\vec{V}_{measured} = \vec{V}_{SC} + \vec{V}_{Wind} \quad (1)$$

where $\vec{V}_{measured}$ is the measured velocity, $\vec{V}_{SC}$ is the spacecraft velocity and $\vec{V}_{Wind}$ is the atmospheric flow velocity. To achieve an attitude induced velocity error of 40 m/s, the spacecraft attitude knowledge must be 18 arc-seconds or better as described by the following equation

$$\theta_{req} \le \arcsin\left(\frac{\vec{V}_{Wind\_error}}{\vec{V}_{SC}}\right) \quad (2)$$

where $\vec{V}_{SC} = 8000 \text{ m/s}$ for LEO.

Both EO and Space Weather missions have been proposed as likely candidates for constellations. A constellation of EO satellites would enable fast ground track repeat times and support disaster monitoring applications[8].

One of the compelling cases for a Space Weather constellation is the ability to measure the horizontal wind field at a diversity of spatial locations and local times. A star tracker capable of providing attitude solutions in the 20 arc-second range will support such constellation missions.

Space Situational Awareness

Space situational awareness missions can be separated into two general categories. The first being a survey mission to characterize debris in LEO, MEO and GEO. One such mission is the Space-based Telescope for the Actionable Refinement of Ephemeris (STARE)[9]. Such missions typically have a telescope with a small field of view, similar to astronomy missions, because pointing knowledge has typically only been a few arc-minutes, only objects that are closer and significantly brighter can be imaged. A precision star camera could significantly expand the capabilities of nano-satellite survey missions. .

A second SSA type mission is the detection of an object in the vicinity of the primary bus. High precision pointing and a camera that can image the approaching object are of interest. While detection of an approaching hostile system may be best done using radar, the characterization can most readily be accomplished by a ground operator analyzing a visual image. The ability to operate a star camera both as a sensitive camera for attitude determination and as a basic imaging system is of significant value to small satellite SAA missions that are mass, volume and power limited. A dual use star camera would provide significant utility to such missions.

Proximity Operations

In addition to SAA missions, constellation missions that require relative navigation, proximity or docking operations would clearly benefit from a star camera that can provide precise attitude knowledge and imagery for pose determination.

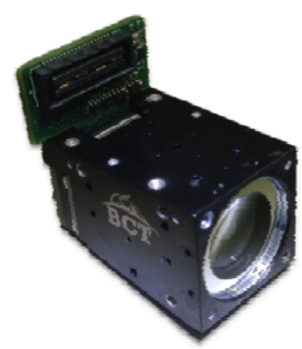

Figure 1: BCT Nano Star Camera

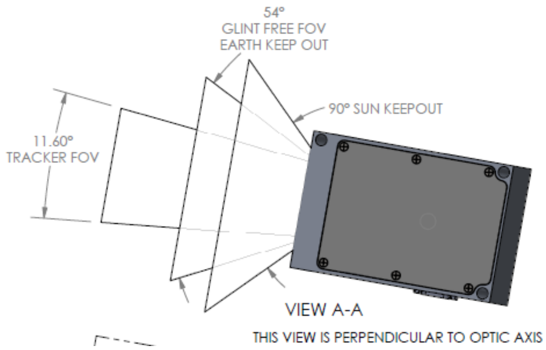

Figure 2: BCT Nano Star Camera viewing geometry

BCT NANO-STAR CAMERA 1 (NSC-1)

The Blue Canyon Technologies Nano Star Camera 1 is a reliable, high performance design, compatible with a variety of CubeSat and Nano-sat configurations and missions. The camera contains a low-light sensitive detector with the ability to detect stars down to a 7.0 magnitude. The on-board software includes a star catalog that contains greater than 20,000 stars, and includes a lost-in-space star identification algorithm. The camera is designed with an easy to integrate digital interface electronics, and is contained within an extremely compact package. A picture of the camera shown in Figure 1 and performance details are provided in Table 1.

Table 1: Nano Star Camera Performance Summary

Specification	NSC-1 Performance
Attitude solution update rate	5 Hz
Cross-axis Accuracy	7 arc-sec (1σ)
Accuracy about roll axis	24 arc-sec (1σ)
Time-to-first-fix	2 seconds
Field of View	11.6° x 9°
Mass	≤ 0.5 kg[1]
Volume	≤ 5 x 5 x 10 cm[1]
Nominal Power Consumption	≤ 0.5W
Operating Voltage	5 +/- .1 Vdc
Data Interface (optional control electronics)	RS-422, I2C or SPI

1 – including baffle

The BCT Nano Star Camera contains an optical detector that accurately measures the positions of stars which enables precise 3-axis stabilization of a spacecraft attitude. The camera uses an internal baffle to prevent interference from stray light sources, and a built-in algorithm to select appropriate stars for use in the solution. The star camera outputs the sensor orientation compared to an inertial reference.

The BCT NSC-1 can be used as a stand-alone component, as shown in Figure 1, or it may be included in BCT's complete attitude determination and control system (XACT). Both types of systems are being integrated into future missions.

The NSC-1 has an asymmetric 11.6° by 9° (10 mill-steradian) field of view with a 54° glint free and earth keep out zone along with a 90° sun keep out zone as depicted in Figure 2.

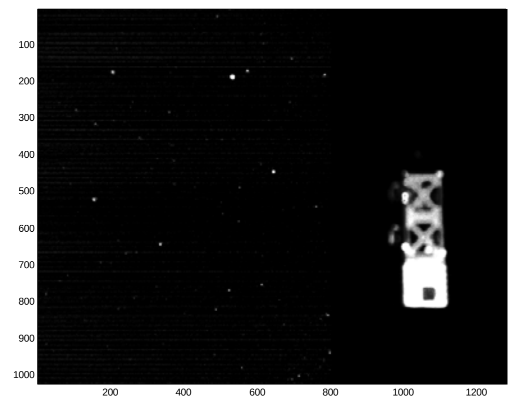

Figure 3: NSC-1 star field with pose image overlay

Constellation Features

shows a snapshot of stars moving across the star camera FOV at orbit rate and a 3U cubesat rotating in the corner of the FOV. This demonstrates the ability of the NSC-1 to support multiple regions of interest by providing composite images that combine star field images using long exposure times and high-gain linear scaling with target object images using short exposure times and low-gain logarithmic scaling. The NSC-1 takes back-to-back images – one for attitude with optimal settings determined by the tracker itself, and one with settings commanded by the user, based on the characteristics of the target object to be viewed. The composite image is then provided to the user for use in RPOD algorithms such as pose determination.

Example images indicating the resolution and clarity for pose determination are shown in the following figures. Figure 4 shows a full-scale mock-up of Mariner 7, taken in full daylight with a 4-microsecond integration time. Figure 5 shows an automobile at night, illuminated by a street lamp, using a 50 millisecond integration time.

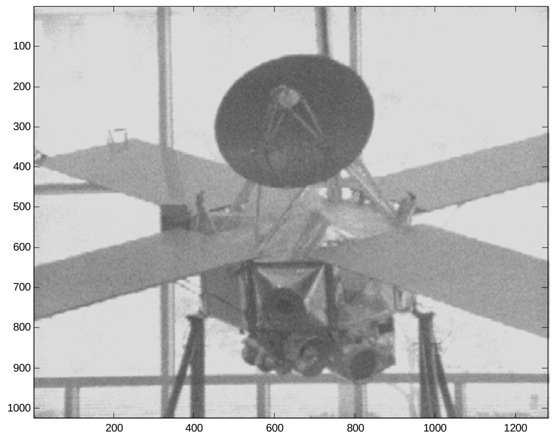

Figure 4: Image of Mariner 1 taken with NSC-1.

Figure 5: Picture of an automobile take at night with NSC-1.

Both of these figures exhibit the capability of the NSC-1 to be operated in camera mode and provide images for pose determination.

NSC-1 PERFORMANCE

The BCT Nano Star Camera (NSC-1) is constructed around a set of key elements. These include the integrated baffling system, the optical components, the imager, a star detection algorithm, a star centroiding algorithm and a geometric projection algorithm. These system elements are discussed in the following sections.

Lens Barrel

The NSC-1 Optical assembly was designed specifically with CubeSat or other microsat applications in mind. It was intended to be a small, light, and inexpensive optical system for use over a wide temperature range. The lens assembly itself consists of a minimum number of elements that support rapid, high-volume assembly, providing the desired centroid performance. The system is robust enough in design that it requires no active alignment during assembly and instead relies on simple mechanical tolerances. The qualities that make this possible also make the lens athermal in its performance over a large temperature range, -30 to +60 °C. The lens system creates a tuned point spread function to optimize the per star centroiding.

Figure 6: BCT Nano Star Camera Baffles

Baffle

To ensure excellent performance of the NSC-1, a baffle has been designed and integrated into the system. Figure 6 is an image looking off-axis into the NSC-1 baffle system. Only the first few baffles are visible. The entire baffle system has been coated to reduce the potential of stray light on the detector thus impacting the system performance. The baffle design utilized Zemax and was performed iteratively to account for issues such as manufacturing defects, dust on the optics and imperfections in the baffle coatings. The NSC-1 baffle is approximately 1” x 2.6” x 2” and fully integrated into the unit.

The lens baffle system was designed to enable nominal operations with a sun keep out half-angle of 45 degrees and an earth keep out half-angle of 27 degrees. To achieve this level of performance the scattered light hitting the detector must be minimized. To maintain the star camera performance, the scattered light from the earth must be reduced by more than 7 orders of magnitude and the scattered light from the sun must be reduced by 10 orders of magnitude. Figure 7 shows a numerical simulation of the baffle performance using the current NSC-1 baffle design and Zemax. The baffle performance for 0.62π steradians (160°x60°) around the star tracker bore-sight is shown in Figure 5a along with the earth and sun keep-out zones. Figure 5b is a cross section of the baffle extinction along the two primary axes of the star camera. The baffle rejection exceeds 30dB within 2° of the star camera field of view and drops rapidly 22-24° off axis. Note that because of the asymmetry in the camera field of view the two curves for the vertical and horizontal baffle performance are not identical. For the sun keep-out zone the average extinction is -77dB at 27° and for the sun keep out zone the average extinction exceeds -100dB. The baffle performance asymptotes to approximately -108dB at an angle normal to the boresight. Baffle performance verification tests will be performed during the summer of 2013 using a heliostat.

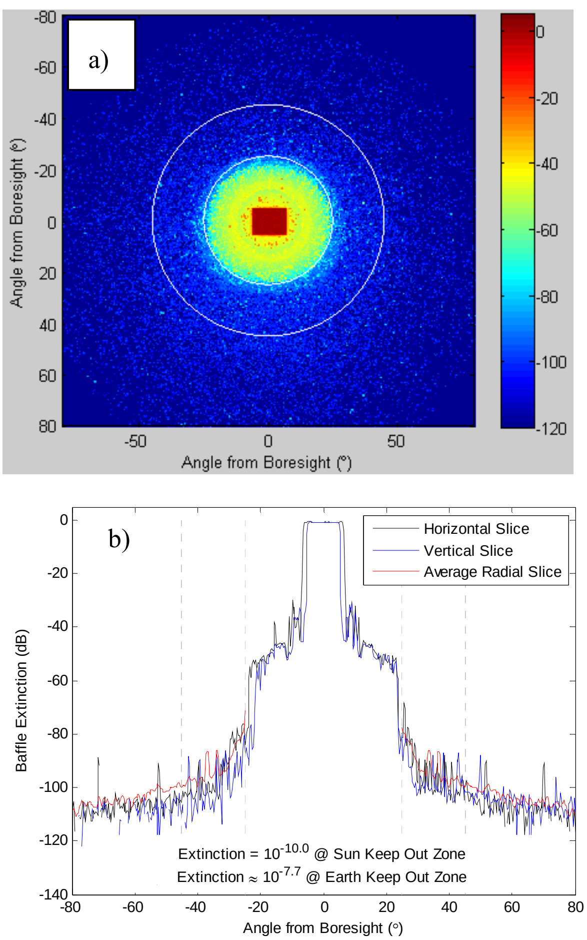

Figure 7: Baffle extinction versus field of view (top) and cross sections (bottom).

Star Fields

To demonstrate the performance and sensitivity of the camera we have collected a number of data sets. Figure 8 shows an example star field image collected with the NSC-1 from the ground in the Boulder, Colorado area. While aerosol scattering, scintillation and local light contamination impact the quality of the image, one can get an idea of the number of stars seen in the camera field of view (11.6°x9°) from this image.

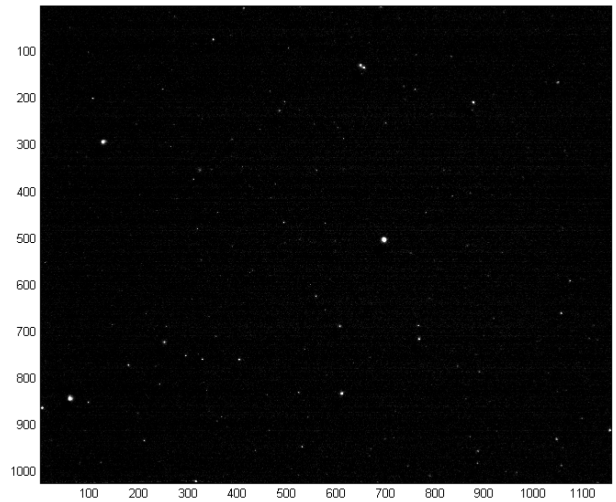

Figure 8: NSC-1 star field image

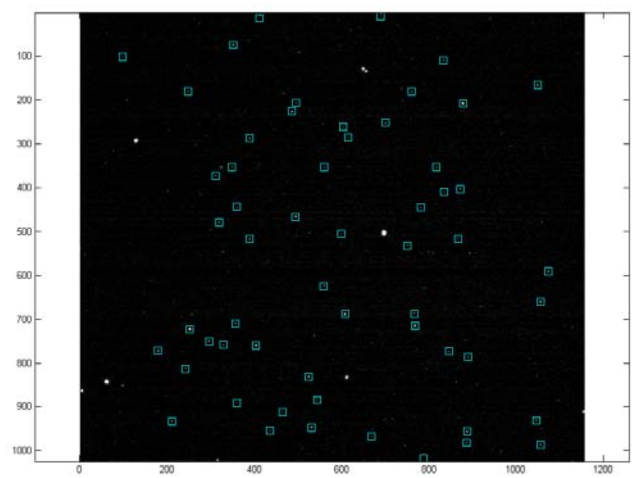

Figure 9: NSC-1 star field image with selected stars

Figure 9 is identical to Figure 8, however the stars selected for the attitude solution are indicated by the square symbols. Stars that are too dim and don't meet a predefined signal to noise ratio are excluded from the solution, as are stars that are too bright or too-close to their neighbor, all of which can negatively impact the attitude solution.. All of the star selection, centroiding and processing occurs on the dedicated processor within the NSC-1. The user also has the option of commanding the NSC-1 to use specific stars in the FOV; this is helpful when performing repeated inertial attitude measurements over different periods of time, since any residual catalog or calibration errors would be repeated in each measurement.

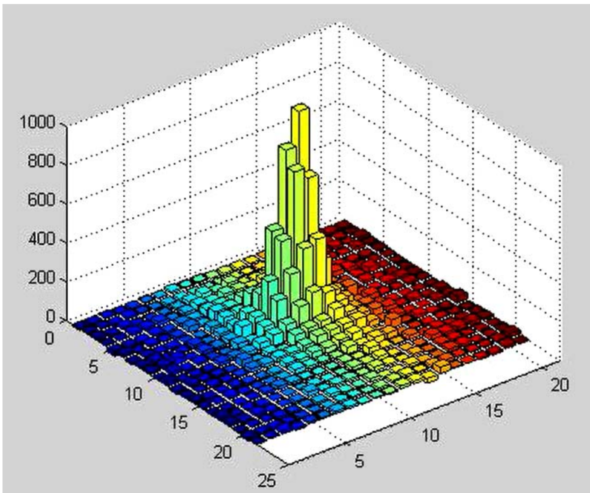

Figure 10: Energy distribution of a magnitude 6.4 star.

One of the key performance drivers for a star camera is the signal to noise ratio. If the imager is noisy, either due to thermal noise or readout noise, the ability of the system to detect and centroid stars is reduced. Additionally if the transmissivity of the system is not carefully considered then the number of photons reaching the imager will be reduced resulting in a reduction of system sensitivity. This directly impacts the ability of the system to detect dim stars.

Figure 10 shows the energy distribution of a magnitude 6.4 star as observed on the NSC-1 imager using nominal gain and integration settings. . From Figure 10 one can see that the magnitude 6.4 star is clearly detectable well above the surrounding background level. The peak pixel intensity to average surrounding noise level exceeds 25dB. This excellent performance enables NSC-1 to use stars down to magnitude 7 and provide precise attitude solutions.

Attitude Solution

The performance of system is demonstrated with an attitude solution computed using the NSC-1 and shown in . To compute these results 30 images were collected with the NSC-1 at one second intervals while the star tracker was stationary. The mean earth motion during this interval was removed and the residual deviations are plotted in . From these results the RMS values for each of the x, y and z axes were computed. The results were 2.4, 2.0 and 7.4 arc-seconds respectively. By including other error sources, such as low-frequency calibration residual errors, we arrive at the conservative pointing accuracies noted in Table 1.

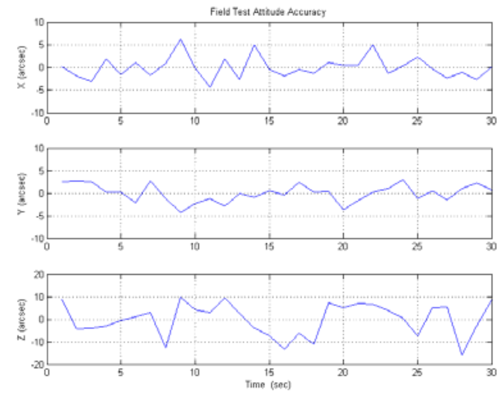

Figure 11: Attitude Deviation from the Mean Motion

Operational Modes and Timing

As was shown in , the NSC-1 has multiple operational modes with the ability to operate as a standard star camera, an imager or, or overlay an image on the background star field. The modes of operation are star tracker mode, camera mode, region of interest (ROI) image overlay mode or space situational awareness (SAA) mode. Since the exposure time and image intensity will vary dramatically, the user has the ability to set the analog gain, exposure time and scaling option (linear or logarithmic) in camera mode. In this mode the user can define a region of interest and select an integration time from 4 micro-seconds to 1 second. Consecutive images are limited by a combination of the device readout time and the integration time. To achieve consecutive images at a cadence shorter than 30ms requires the selection of a region of interest (ROI) on the image.

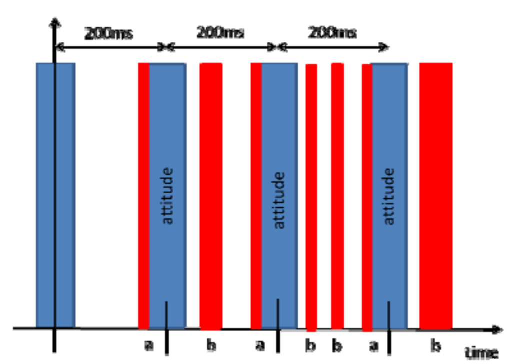

Figure 12: NSC-1 notional timing diagram.

Figure 12 shows a notional timing diagram for the NSC-1 toggling between nominal star tracker mode and camera mode. The integration time and gain settings for star tracker mode are set automatically by the NSC-1 and adapt to provide the required level of performance. Running at a typical 5Hz update rate the blue areas in Figure 12 indicate when the NSC-1 is operating in start tracker mode. The red areas indicate when the NSC-1 is operating in either camera or ROI image overlay mode. In ROI image overlay mode, shown in , the NSC-1 takes an exposure with a set of user defined settings immediately before the normal star camera exposure, these are denoted by (a) in the figure. These two images are overlayed and returned to the system as a single integrated image. By taking two exposures the bright camera image is not saturated by using the short user defined exposure time and the dim stars are visible using the longer star camera mode exposure time. When operating in camera mode as denoted by (b) in the figure, the user can take multiple images between star camera images. The integration time, image scaling and analog gains are user selectable for each image and can be rapidly changed between images.

When operating in SAA mode the system will utilize the nominal star tracker images. However during the image processing and star identification process any objects that are moving relative to the star background will be tracked and reported to the system.

Integration and Test Features

The NSC-1 also features a high-speed test port which interfaces with an optional GSE computer for use in closed-loop testing prior to launch. The GSE computer sends images to the NSC-1 via the test port. The GSE computer can send either pre-loaded images, containing star fields and other objects, or simulated star field images that are created real-time, based on attitude data provided to the GSE or by the user's real-time simulation environment.

BCT is also beginning the development of software to generate real-time images of other satellites for use in closed-loop formation flying. The user inputs satellite information from a CAD model, then during the simulation, the GSE computer uses real-time attitude and position data for both the host and target satellites to generate the images as the NSC-1 would see it on orbit (similar to that in Figure 3).

INTEGRATED ATTITUDE CONTROL SYSTEM

The BCT Nano Star Camera is included in BCT's XACT unit (Figure 13), a complete CubeSat precision attitude determination and control system, and the XB1, a complete 1U CubeSat Bus (shown in Figure 14).

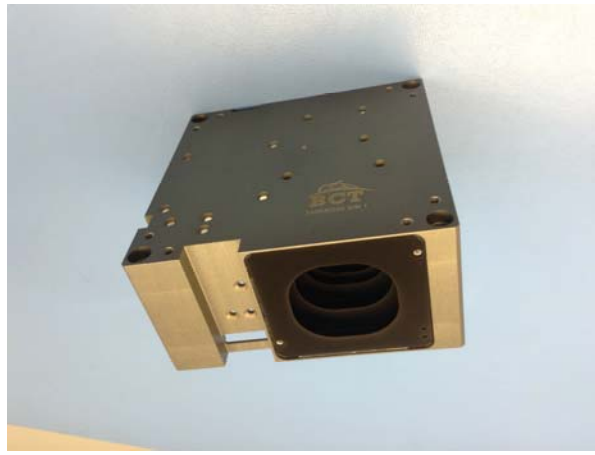

Figure 13: XACT, A complete CubeSat ADCS

BCT's XACT features 3-axis stellar attitude determination in a micro-package. Built-in, flexible commanding allows for multiple pointing reference frames: Inertial, LVLH, earth-fixed, and solar. Precise control is provided by low jitter 3-axis reaction wheels. User friendly software is provided for simulation, integration, and customization of the XACT System.

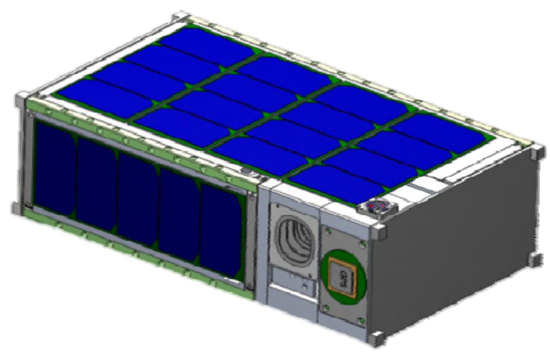

Figure 14: XB1, A 1U CubeSat Bus Shown in a 6U Configuration

The BCT XB1 provides a complete CubeSat bus solution in a highly integrated, precision platform including: Ultra-high-performance pointing accuracy, robust power system, command and data handling, RF communications, propulsion interfaces, and multiple flexible payload interfaces; precision stellar-based attitude determination & control provided by dual star trackers; supports precision orbit propagation of multiple target objects, with flexible pointing commands to enable a wide range of missions. The XB1 Flight Software and Simulation environment supports user-developed flight applications unique to your mission.

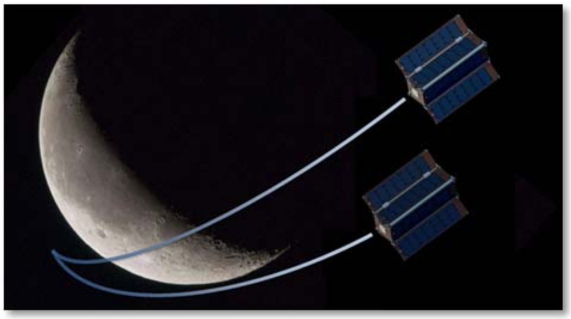

Figure 15: NASA INSPIRE Cubesat Mission

UPCOMING MISSIONS AND APPLICATIONS

Two of the BCT Nano Star Cameras are being flown on the NASA JPL INSPIRE mission, which will be the first CubeSat Mission to leave Earth's orbit for interplanetary space. The mission will demonstrate functionality, communication, navigation, and payload-hosting in deep space. BCT developed its high performance, micro-sized star cameras specifically for use on missions like INSPIRE that use small spacecraft to perform missions traditionally accomplished with larger, more expensive systems. The INSPIRE mission is expected to launch in 2014.

The BCT XACT ADCS system, which includes the NSC-1, is being used as the ADCS for the Hi-LITE satellite which is a space weather mission designed to study the themosphere and ionosphere. Hi-LITE is being led by the University of Colorado and has been selected by the NASA ELaNa program for a future launch.

The BCT Nano Star Camera is also being flown in the fall of 2013 aboard a NASA sounding rocket flight as part of an instrument suite demonstration in partnership with the University of Colorado's Laboratory for Atmospheric and Space Physics (LASP).

CONCLUSIONS

We have presented details of the BCT Nano Star Camera 1 (NSC-1), which is a highly capable multifunction star camera. Operating in star camera mode it can detect stars down to magnitude 7.0 and can provide attitude solutions of 7 arc-seconds RMS. This level of pointing enables constellation missions for earth observing and space weather. In addition to nominal star-light-in-quaternion-out operation, the NSC-1 can also operate in a number of additional modes that support space situational awareness and proximity operations. In SAA mode the NSC-1 will provide output information about objects are not in a stellar fixed coordinate frame. In camera mode the system can operate as a digital camera with a range of integration times, output scaling and analog gains. The final mode of operation in the ROI overlay mode where an image from a region of interest is overlayed on the background star field. In this mode the star field and overlay images can be acquired with different camera settings.

The NSC-1 is an agile multifunction star camera with arc-second performance that will enable a future class of constellation missions.

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