

Space Validation of the Inertial Stellar Compass

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Abstract. Draper's Inertial Stellar Compass (ISC) is a real-time, miniature, low power stellar inertial attitude determination system, composed of a wide field-of-view active pixel sensor (APS) star camera and a microelectromechanical system (MEMS) gyro assembly, with associated processing and power electronics. The integrated APS and MEMS gyro technologies provide a 3-axis attitude determination system with accuracy better than 0.1 degree at very low power and mass. The attitude knowledge provided by the ISC is applicable to a wide range of space missions that may include the use of highly maneuverable, stabilized, or even tumbling spacecraft. Under the guidance of NASA's New Millennium Program's ST-6 project, Draper has developed and now flight validated the ISC. Its completion via flight validation represents a breakthrough in real-time, miniature attitude determination sensors. This paper describes the space validation component and initial on-orbit results of the ISC.

Introduction

The ISC is an innovative attitude determination sensor that combines MEMS and APS technologies in an integrated package to produce a real-time, robust attitude solution and body rate estimate. Among the key advantages of the ISC are its low power, ease of integration with a host spacecraft, and ability to maintain better than 0.1° accuracy during high rate maneuvers. Key ISC performance features include:

- Better than 0.1° accuracy (each axis)
- High-rate maneuver capability (up to 40°/sec)
- Self-initialization (over 99% of the sky)
- Low Mass ~ 2.9 kg
- Low Power ~ 3.5 W
- Flight Proven

This paper provides an overview of the space validation effort of the ISC and puts forth initial on-orbit results obtained by the ISC. These on-orbit results have now validated this new class of attitude determination sensor. Through space validation, NASA's New Millennium Program's ST6 Project has provided a direct technology infusion path for the ISC. This multi-year effort has now brought a new and useful technology to future spacecraft designers to incorporate into their designs. In addition, the success of the ISC marks for the first time the successful use of MEMS gyros in space demonstrating that MEMS devices have a promising future in space given their inherent low power and low mass qualities.

Technical Overview of the ISC

The ISC consists of two separate units (as shown in Figure 1), connected by a cable: the Camera Gyro Assembly (CGA), which contains the MEMS and APS sensors, and the Data Processing Assembly (DPA) containing the sensor's embedded computer, software, and power supply electronics. The two-unit design facilitates easier integration with a host spacecraft. Only the CGA needs to be precisely aligned with the host spacecraft using the reference cube located on the CGA housing. The modular design was emphasized for operability by allowing concurrent development and testing of the two units. In addition, the modular design supports interesting future applications and variations of the ISC.

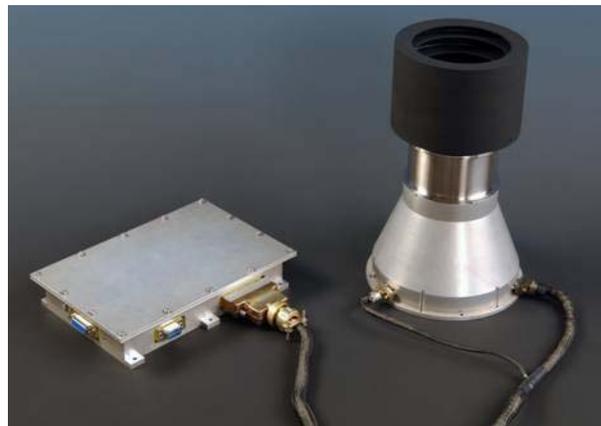


Figure 1: ISC Flight Unit

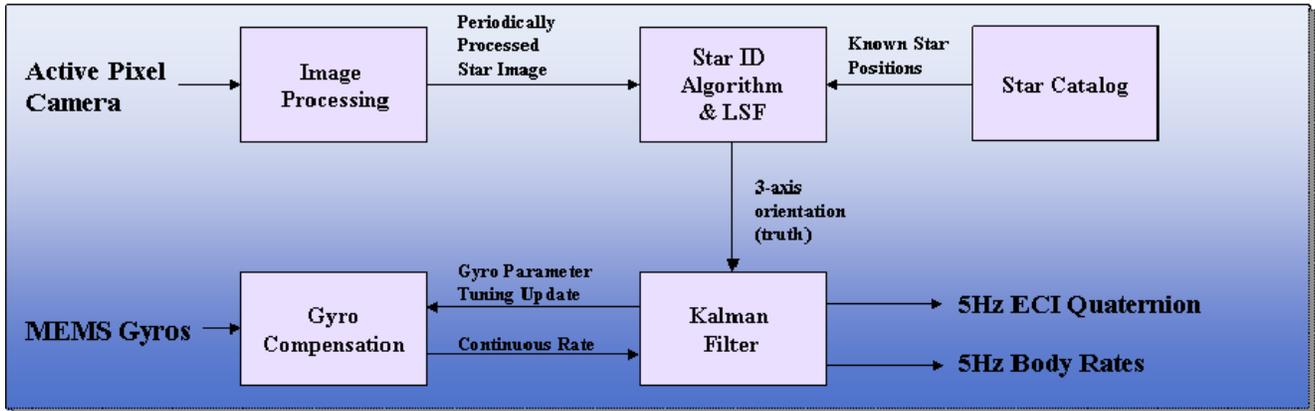


Figure 2: ISC Functional Block Diagram

A simplified ISC system data flow is described in Figure 2. During operation, attitude information is propagated by the ISC's MEMS gyros resident in the CGA. The tuning fork gyros built by Draper Laboratory sense inertial rates that are sampled at a high frequency (320 Hz). The tiny gyro sensors are etched in silicon using a Draper-developed MEMS process. A sense mass is driven into oscillation by electrostatic motors. The mass oscillates about one axis and as the body is rotated, the Coriolis effect causes the sense mass to oscillate out of the plane. This change is measured by capacitive plates and is proportional to the rotational rate of the body. The raw gyro data is then compensated and processed through an extended Kalman filter to produce a 5Hz attitude quaternion and corresponding body rates. The star camera is used periodically (every 30s) to obtain a camera quaternion that enables the gyro errors to be removed and the inherent drift of the gyros to be calibrated and compensated. Stars in the image are identified using a lost-in-space (LIS) attitude determination algorithm that analyzes the image against a stored star catalog to identify the camera's orientation without any prior knowledge of the spacecraft's attitude.[1] Once initialized, the gyros are then used to maintain attitude knowledge continuously until the next stellar update can be obtained to further support gyro compensation. The complementary use of gyro and camera data help the spacecraft overcome difficulties in providing attitude knowledge during transients, high slew rates (up to 40°/s), or periods of star camera occlusion.

The unique and innovative nature of the ISC has resulted in an international patent awarded to Draper Laboratory in 2007. The USPTO on-file patent description further describes the technical operation and lengthy technical details of the ISC.[2] Additionally, an ISC overview and some of its potential applications

have also been well described with prior published papers by the authors.[3] [4]

Validation Approach

Validation Objectives

The ISC program set forth a set of objectives in order to demonstrate its successful operation in the necessary relevant space environment. All objectives were achieved within the union of ISC ground and flight campaigns. The ISC validation objectives, New Millennium Program (NMP) requirements, and associated ISC measurements are shown in Table 1.

Objective	Where Tested	NMP Requirement	ISC Measurement
Accuracy (1-sigma) in each axis with slewing < 40 deg/s	Ground & Flight	0.1 degrees	<0.1 degrees
Self-initialization	Ground & Flight	< 10 min over 90% of sky	< 5 min over 97% of sky
Power	Ground	< 4.5 W	3.6 W
Mass	Ground	< 3 kg	2.9 kg
Space Qualified	Flight	Operates in Earth orbit environment	Operates in Earth orbit environment

Table 1 – ISC Validation Objectives

Ground Validation

Prior to launch, the instrument was extensively tested through a rigorous ground validation campaign and demonstrated exceptional results. The ground validation of the ISC was conducted in an orderly and thorough fashion to significantly raise its Technology Readiness Level in preparation for space validation and also to maximize the chance of on-orbit success. To the greatest extent possible, the allocation of validation tests was biased toward ground testing for better visibility and control of the system as well as assurance of test completion. These are well described in a prior AIAA published paper on the subject matter.[5]

Space Validation

NASA's New Millennium Program's ST6 Project has provided a direct technology infusion path for the ISC by supporting space validation. Space validation is a necessary component of the NMP completion. The successful completion of the ISC space validation has brought a new and useful technology for future spacecraft designers to incorporate into their missions.

During the ISC validation flight, specific on-orbit tests described later in this paper have verified the performance of the Draper Laboratory built MEMS gyros, APS star camera, and the overall performance of the ISC. The angle random walk (ARW), scale factor, and bias stability for the MEMS gyros have all now been characterized in space. The ISC's predicted camera performance has also been validated in the relevant space environment with great success. Finally, the integrated performance of the MEMS gyros and APS star imager has been demonstrated under various 3-axis maneuver profiles meeting the 0.1 degree requirement levied by the NASA program office.

Host Spacecraft Overview

TacSat-2 Vehicle

TacSat-2 space vehicle (SV) was selected by the NMP to be the host carrier for the ISC. The primary mission of the 350kg Air Force spacecraft launched December 16th, 2006 is to obtain 1m visible imagery and couple this with RF geolocation capability. It was launched into a 400km circular orbit via an Orbital Sciences built Minotaur Rocket (figure 3). The TacSat-2 mission marked the first rocket flight into orbit from NASA's Wallops Island since 1999, when an air-launched Pegasus rocket hauled seven communications satellites into space. The last ground-based space launch attempt was more than 11 years ago, and the most recent successful orbital launch before TacSat-2 was in 1985.

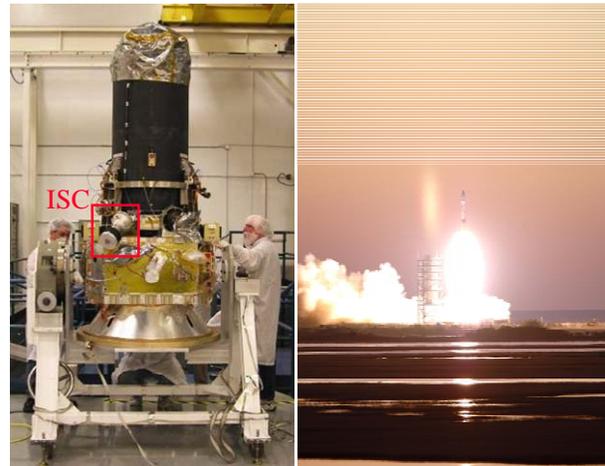


Figure 3: ISC on TacSat-2 Spacecraft and TacSat-2 Launch on OSC Minotaur Rocket

The TacSat-2 SV was also developed by the Air Force to demonstrate advanced technologies. It hosted 11 different payloads to be validated, the ISC being one of them.[6] The TacSat-2 vehicle is the preliminary step in achieving the Air Force goal to obtain a rapid response from space. The spacecraft was conceptualized in 2004 and demonstrated a quick storage to on-orbit functionality in less than month. Additionally, a quick on-orbit commissioning was demonstrated.

The three-axis stabilized spacecraft served as a superb validation platform for the ISC since the spacecraft was designed to point at various inertial locations on demand with a moderate slew rate capability (up to 1 degree/sec). Additionally the spacecraft had a real-time data capability that made monitoring of ISC on-orbit operations more timely and intuitive. Finally, since a primary goal of the TacSat-2 mission was to validate technologies, planned spacecraft operations were catered specifically to the various instrument teams making the ISC validation an efficient process.

On-Orbit Results

Planned Operations

Prior to launch, the ISC ground validation campaign had achieved the majority of its required objectives as defined by Table 1. The notable exceptions were to validate star camera operation over greater than 90% of the sky (ground testing was limited to the Northern Hemisphere of the Earth) and to meet attitude performance goals while in orbit onboard the space vehicle.

A series of SV flight operations or ISC “objective elements” (OE) were planned for the ISC over a three month period. A series of these objective elements were executed to validate both the star camera and overall attitude performance of the ISC while on-orbit.

ISC Functional Checkout

The ISC was powered on for the first time on December 27th, 2006 at 18:52 Zulu. Careful inspection and analysis of ISC telemetry, confirmed that all subsystems of the ISC were fully operational and indicated a clean bill of health. The ambient thermal conditions to the ISC were within margin with an average CGA baseplate temperature of 8° C in the unpowered state, and 15° C in the powered state. Active heating through an SV baseplate heater was not required to the ISC due to the effective thermal blanket insulation of the CGA and via self-heating of the unit when powered on.

CGA monitored current draw indicated that all electrical systems were nominal and that all cables (internal and external) were in tact. The SV avionics software that commands the ISC and acquires its data was also operating nominally. The SV downlink suffered initially from a ground error that would non-robustly handle downlink CRC errors. The problem manifested itself with zeroed out packets in some ISC data and downlinked imagery. This problem was eventually fixed within the ground operations software.

ISC Accuracy Performance during Inertial Hold

On December 28th, the spacecraft positioned the ISC to an anti-nadir orientation and performed an inertial hold to the constellation Leo. The ISC collected data in a low data rate background mode, correctly identified the slew maneuver, and most importantly, correctly identified its ECI attitude to better than 1/10th of a degree.

Performance of this initial run is shown in Figure 4. The green dots represent ISC star camera attitude, the red dashes indicate the 1/10th of a degree performance bounds, and the blue lines represent the integrated attitude of the ISC. By comparing the deviation of the integrated attitude to that of an interpolated line fit attitude between camera updates, one can then obtain a “self-score” measure of attitude performance. This first run indicated a performance of 0.037° in pitch, 0.036° in yaw, and 0.038° in roll. These numbers do not account for the a-priori measured camera errors of 0.005° in pitch, 0.005° in yaw, and 0.01° in roll, bringing the total self-score performance to 0.042° in pitch, 0.041° in yaw, and 0.048° in roll.

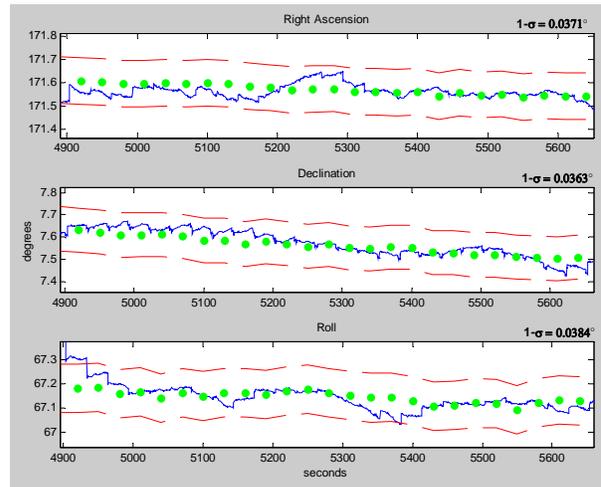


Figure 4: Initial on-orbit performance run of ISC 12/28/2006 during TacSat-2 inertial hold maneuver demonstrating 0.1° ISC performance accuracy. Integrated ISC attitude is shown in blue, star camera attitude is shown in green, and 1/10th degree performance error bounds are shown in red. Slow drift in SV attitude during inertial hold was verified in TacSat-2 body rate data.

During a live real-time pass of the SV within this same run, the ISC was commanded by onboard autonomy to go into a high data rate diagnostic mode in order to collect an image and high rate diagnostic data while pointing to the stars. This initial image was collected and analyzed, the data of which indicated that the camera system was fully operational and intact. Detailed ground inspection of the image showed that the lens was mechanically sound, the APS imager performing nominally, and the star camera software was able to initialize the attitude of the ISC correctly without external aid. This initial image was also used to independently compare, to the first order, that the reported onboard ISC camera attitude matched the attitude independently calculated in the downloaded image. This method, known as “self-score”, would be used extensively throughout the space validation mission where the prior calibrated star camera attitude data product independently corroborates the integrated attitude of the ISC.

Additionally for this run, a comparison of the ISC attitude to the integrated spacecraft attitude was done. The integrated spacecraft attitude was made up from data generated by an onboard Terma Star Tracker, LN200S IMU, and an onboard SV Kalman filter. The integrated 1Hz attitude was rotated to the ISC body frame and then subtracted for comparison as shown in Figure 5. Comparison with the spacecraft attitude was well within the 1/10th of a degree requirement (0.059° in pitch, 0.052° in yaw, and 0.036° in roll). Differences between self-score performance and independent SV

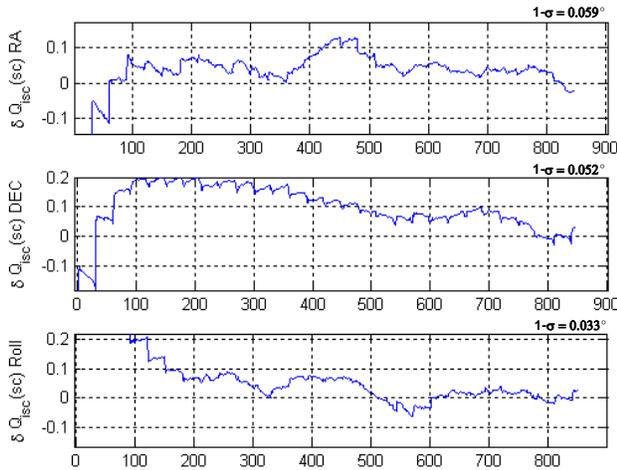


Figure 5: Comparison of integrated ISC attitude data to TacSat-2 integrated attitude data for an initial run. Plot shows ISC accuracies are well within 1/10th of a degree requirement when compared to the independent SV attitude source.

performance can be attributed to minor mechanical fluctuations in the SV bracket that holds the CGA and also to inherent errors in the SV attitude determination system.

The ISC database contains many more background runs that are typical of the run previously described where the SV was commanded to go to specific inertial positions and the ISC collects data at these various inertial locations. Inertial locations were varied in order to characterize performance in star fields with various luminosities and orientations. In fact, of the 1500 stars that are located in the embedded ISC star catalog, 97% of them have been successfully identified. The remaining 3% are not identified only because they have not been within the FOV of the ISC camera to date.

ISC Data Collection during Serendipitous Maneuvers

The ISC continues to collect valuable background mode data used for long term performance analysis during “serendipitous maneuvers” on the SV. For example, during an experimental ion thruster checkout (known as HET), the ISC benefited from its determined orientation by seeing a long run of stars devoid of Earth, Moon, or Sun interference (referred to as occultations). The ISC also detected these HET firings via its internal rate gyros. Additional maneuvers needed by other SV payloads resulted in various ISC data collections that have long runs devoid of occultations, large changes in

subtended angle, and are pointing to various portions of the sky. All of these continue to be very valuable and have resulted in a large ISC database of performance over various conditions.

ISC Accuracy Performance during Slew Maneuvers

To meet a level 1 requirement, it was necessary to characterize the ISC while the SV was slewing to different portions of the sky. In this mode, it is desirable that the SV move as quickly as possible between each instructed inertial hold. Each run involved a series of inertial holds (or dwells) separated with high rate slews in between. The SV dwelled typically for 120 seconds at each prearranged inertial location before slewing to the next location. The number of dwells/slews combination per run varied as did the desired location of the dwell.

The performance of the ISC during a multiple dwell-slew-dwell maneuver was typified during a run on March 29th, 2007. The SV was commanded to slew the ISC to 5 different star fields (Gacrux, Spica, Menkent, Shaula, Antares) with 11 different high rate slews. The complicated maneuver was sensed with the MEMS gyros and is illustrated in Figure 6.

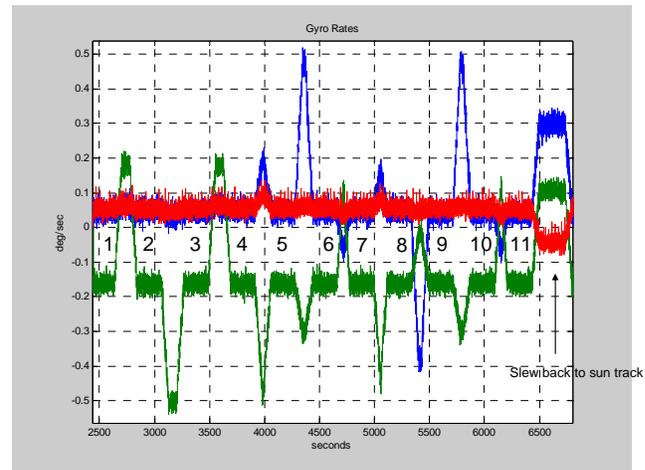


Figure 6: Raw ISC MEMS gyro output during a complicated multi-slew SV event. The ISC gyros can sense SV movement up to 40°/second. For this run, all rates were below 1°/second and the spacecraft was commanded to point to 5 different star fields (Gacrux, Spica, Menkent, Shaula, and Antares).

During the slew to the various star fields, the ISC continued to maintain its attitude to better than 1/10th of a degree. Figure 7 shows the reported right ascension, declination, and roll reported from the ISC during the complicated maneuver.

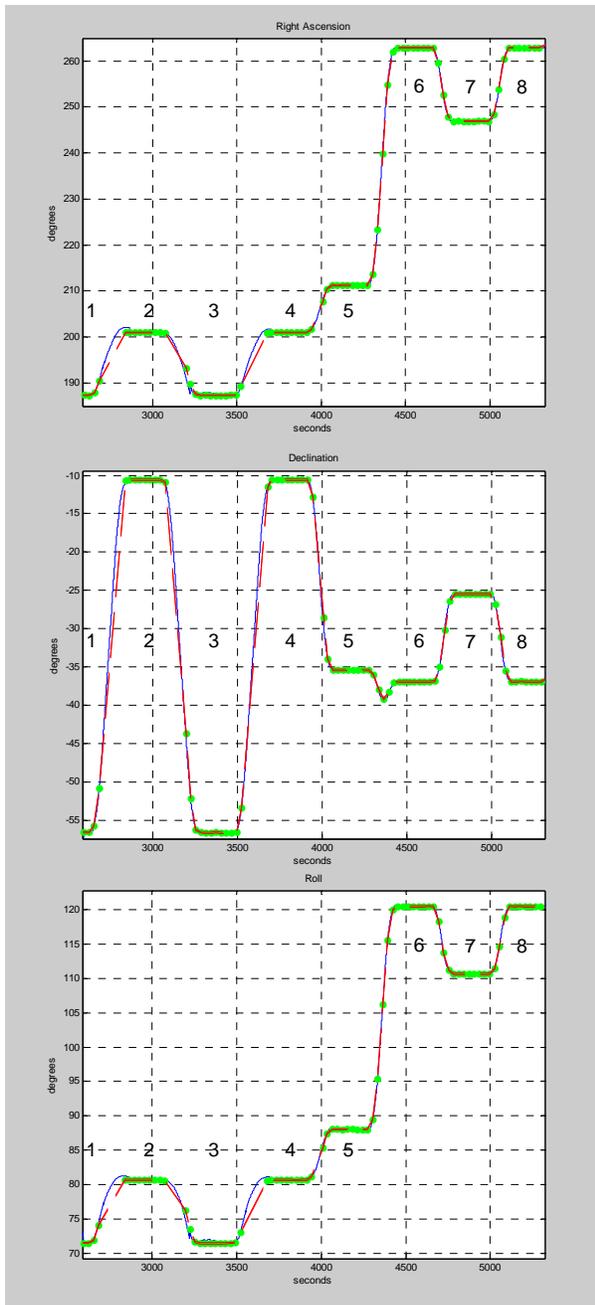


Figure 7: Respective right ascension, declination, and roll output from the ISC for a complicated maneuver that involved five different star fields over large angles between them. ISC integrated attitude (blue dots) accuracy is better than a 1/10th of degree when compared to reported ISC star camera attitude shown as green dots.

The particular run was challenging since the SV subtended large angles at high rates in the sky between inertial holds on various star fields. Figure 8 indicates the errors between the reported spacecraft attitude and the ISC attitude for the previously described run. The

plot indicates that the ISC can meet its performance goals during multiple slews, various star fields, and at rates approaching 1 degree/second.

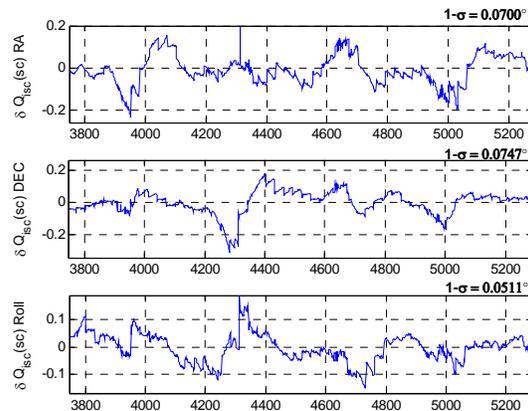


Figure 8: Error difference in each axis between reported SV attitude and ISC reported attitude in ISC body frame. Accuracies of 0.07° in pitch, 0.07° in roll, and 0.05° in roll all well below the 0.1° required.

During many of the slew-dwell-slew maneuvers, the ISC was commanded, while in diagnostic mode, to gather detailed data on ISC filter performance, gyro performance, and to allow for raw image capture. Additionally, the MEMS gyros have proven to be stable, indicating no change in bias, scale factor, or angle random walk as compared to ground validation data.

Multiple images have been taken in diagnostic mode while on-orbit to validate ISC star camera performance. These images have been independently calculated on the ground to determine attitude at a specific point in time. This attitude was then compared to the reported ISC star camera attitude at that specific point in time. With over 30 images calculated, the error difference between the two sources did not deviate from what was tested on the ground (18" pitch, 18" yaw, 36" roll). A downloaded image of Capella is shown as reference in Figure 9. This image shows typical ISC camera sensitivity of the star camera down to visual magnitude 6. This is about half of an order of magnitude difference to that of ground testing due to atmospheric attenuation and local light pollution.

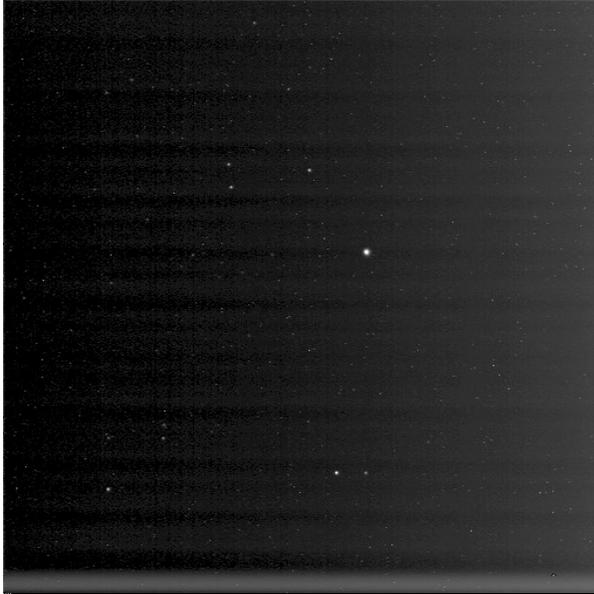


Figure 9: Downloaded raw star camera image of Capella. Images like this were used to independently validate ISC star camera operation by calculating the attitude post-facto on an ISC GSE workstation and comparing it to the reported ISC attitude at the specific point in time. All images correlated to within ground measurement tolerances.

On-orbit Statistics

As of 6/4/2007, the ISC has been operating for approximately 150 days. It has spent 98% of its time in background mode as compared to the high data bandwidth diagnostic mode. There have been 29 power cycles of the ISC during various SV safe hold mode scenarios. Over 31 megabytes of dedicated diagnostic data has been collected and over 1.7 gigabytes of background mode data. The reported ISC temperatures have been between 5° C and 28° C, all without external heat applied. There have been no patches or changes to the ISC software while on orbit.

Conclusions

Flight testing of the ISC has now qualified the instrument and demonstrated its capability in the relevant space environment. The New Millennium Program has provided the path to validate advanced technologies which have not flown in space, such as the ISC. This development reduced the risk and cost associated with selecting the ISC for future space missions, providing spacecraft designers with the full benefits of this new sensor technology. For an attitude sensor, the ISC's integrated functionality and high-rate

capability are unique and represent a step forward in spacecraft technology that has been demonstrated in space.

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